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The mechanical properties of mine rocks and a standardized test procedure for their determination

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THE MECHANICAL PROPERTIES OF MINE ROCKS

AND A

STANDARDIZED TEST PROCEDURE FOR THEIR DETERMINATION

BY

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A

THESIS

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INTRODUCTION

The problem involves studies of the mechanical properties of rocks and was undertaken in an attempt to determine practical data that will help in estimating the supports required to maintain the roofs of mines during and after mining operations. One of the most important problems in mining today is that of the analysis of the action of mine-rock under stresses. From such an analysis in any given mining venture it should be possible to obtain cheaper methods of mining because the supports necessary to maintain the walls and roof of an excavation may be determined on the basis of how the rock will act under stress. That is, whenever an excavation is made, the roof and walls are under stress, and must be maintained against failure inasmuch as the support originally given by the materials which came from the excavation has been removed.

In addition to mechanical properties of rocks, the physical properties of rock (and ore) are also important factors in determining mining methods, and the amount of support required; in fact, mechanical and physical properties directly affect all phases of mining operations. The term mechanical properties includes: elasticity, plasticity, stiffness, strength, ductility, brittleness, resilience or elastic toughness, and the modulus of rupture. The term physical properties includes: specific gravity, hardness, porosity, and coefficient of expansion. The difference between the mechanical and physical properties is apparent when it is realized that to determine the mechanical properties an external force must be applied. Physical properties are inherent in the rock, and no external force need be applied for their determination.

Research in these fields is necessarily of long range. Over a period of years, rocks can be tested through successive research and eventually a wide range of data will result from which interpretations and conclusions can be drawn. Each test made upon a rock will give data that will allow the rock to be classified as to a certain strength, stiffness, ductility, brittleness, toughness, coefficient of expansion, etc.

The comparatively small amount of literature to be found on the subject dealing with mechanical characteristics of rocks, and the need of standardizing the tests to obtain the data needed for satisfactory interpretations necessitated the narrowing of the problem to tests on six different rock types. From tests made on these rocks, a method of test procedure for determining mechanical properties has been standardized to serve as a guide in future research.

REVIEW OF LITERATURE

A few previous investigations have been made to determine mechanical properties of rock. The investigations can be grouped by their objectives in the following manner: First, those investigations concerned with compressive and tensile strength of the rock and the use of the rock for structural purposes.[1/] Second, those researches in which the purpose was to determine the action of ductile and brittle rocks under large confining pressures.[2/] Third, studies in geophysical exploration which are concerned with the determination of the elastic moduli and wave velocities for seismic waves.[3/] Fourth, investigations made on the physical and mechanical properties of mine rocks[4/] chiefly for the ultimate purpose of obtaining

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1/ Griffith, John H. Iowa Eng. Exper. Sta. Bull. 161, 1937, 56 pp.

2/ Willis, B. and Willis, R. 3rd ed. N.Y. McGraw-Hill, 1934, pp. 1-34.

3/ Heiland, C. A., N.Y. Prentice-Hall, 1940. pp. 452-483.

4/ U. S. Bureau of Mines. Report of Investigations 3891, August 1946. 67 pp.

information that can be applied in judging the support needed to maintain a mine excavation. Standardized test procedures established by these investigations are unsatisfactory for measuring the deformation of the rock specimen as the load is applied.

MECHANICAL PROPERTIES OF ROCKS

General

The mechanical properties of a rock are the characteristics a rock evinces when it is subjected to a force (or forces). They include strength, stiffness, brittleness, ductility, malleability, elasticity, and toughness. The definitions and methods of determining these properties[5/] follow:

Strength

The strength of a rock is the property which determines the ultimate unit stress the material can stand without fracturing. The sub-properties elastic strength, and ultimate strength, also are sometimes used whenever it is necessary to qualify further the broader term, strength. They are specifically discussed under Testing of Mechanical Properties (pg. 9)

Stiffness

Stiffness of a rock is the property that governs the amount of unit deformation per unit stress. Stiffness is measured by the modulus of elasticity (E)* of the material. The modulus of elasticity of a material is the ratio of unit stress to the accompanying unit strain; therefore,

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5/ Johnson, J. B. 6th ed. N.Y. Wiley, 1925. pp. 1-116

Laurson, P. G. and Cox, N.Y. Wiley, 1938. pp. 1-60

Nevin, C. M., N. Y. Wiley, 1931. pp. 1-29.

Boyd, James E., 4th ed., N.Y. McGraw-Hill, 1935. pp. 1-104

* Here, and in subsequent portions of this text where symbols are used, the symbols have been further, more completely defined in Appendix B.

the greater the modulus of elasticity the greater the stiffness of the material.

Elasticity

When a load is applied to a rock it causes a change in the size and shape of the rock. This deformation is called strain. The property whereby a material regains its original size and shape upon removal of a load is known as elasticity.

The opposite property of elasticity is plasticity. A wholly plastic material makes no recovery to its original size and shape upon removal of a load.

Brittleness and Ductility

A brittle rock has a small increment of deformation between the elastic deformation and the deformation at failure; ductile materials have a large increment of deformation between the elastic limit and deformation at failure.

The generally accepted geological definitions of ductility and brittleness differ from those definitions used in describing the effects of brittleness and ductility in metals. The term ductility as used in testing of metals is the property which enables a material to undergo plastic deformation under tensile stress, and it is usually confined to describing materials that can readily be drawn into wires. Malleability is used to define a metal that undergoes plastic deformation under a compressive stress.

Although ductility as applied geologically to rocks does not define the rock as a material that can be drawn into wire, it does define the changes in a brittle rock under large confining pressures. Rocks as are seen at the surface are brittle in that they cannot yield greatly without breaking; but when stressed in all directions so that they cannot separate or break, they yield greatly before fracturing.

Elastic Limit

Elastic limit is the measure of the elasticity of a rock and appears to be the same as the proportional limit. No material is perfectly elastic at all ranges of stress. If a gradually increasing load is applied to a rock, the deformation increases proportionally to the stress set up in the rock until the amount of load is reached above which the proportionality of stress and strain does not exist. Hooke's Law, stress varies as strain, is applicable only to the proportional limit of the material and at this limiting unit stress the rock cannot be stressed without causing a permanent deformation. Above the proportional limit a rock is apparently partially elastic and partially plastic.

Toughness

Toughness is the property that enables a rock to withstand a blow. A tough material is one that can withstand a high stress with a large amount of deformation.

Elastic Toughness

Elastic toughness is the measurement of the amount of energy that a rock can absorb without the stress exceeding the elastic limit.

TESTING OF MECHANICAL PROPERTIES

Compressive Test on Short Prisms 6/

General

A short prism is one with a length less than 8 times its least transverse dimension. A test specimen with an unsupported length greater than

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6/ Johnson, J. B., 6th ed., N.Y. Wiley, 1925. pp. 1-116

Laurson, P. G. and Cox, N.Y. Wiley, 1938. pp. 1-60

Boyd, James E., 4th ed., N.Y. McGraw-Hill, 1935, pp. 1-104

8 times the least transverse dimension will have an increase in eccentricity due to the bending of the specimen, which must be taken into account in determining the allowable load on the specimen. For test specimens with a length less than 8 times the least transverse dimension the effect of lateral deflection can be disregarded in stress computations.

For brittle materials like stone the compression test is of most value in establishing criteria of mechanical properties of materials. The unit stress is found at the first crack, at the elastic limit, if there is one, and at the ultimate strength. The angle of coning, the character of the explosion at rupture, and the shapes of the fragments should all be noted. These criteria assist in determining whether the load was axially or eccentrically applied.

Stress-Strain Diagram

A record of the compression test is kept by observing at increments of 500 or 1000-pound loads the deformation in inches as measured by a deflectometer. The simultaneous readings of load and deformation are recorded opposite one another, and the data of these tests can then be shown graphically by a stress-strain diagram.

In the stress-strain diagram the ordinates are the unit stresses and the abscissae the corresponding unit deformations. After the testing of each specimen, the data recorded must be corrected as to the actual stress per square inch and the unit deformation, inches per inch. As each specimen never measures exactly 1" x 1" x 1", all recorded data of the unit stress must be corrected by the following equation:

$$S = P/A; \qquad (1)$$

where

S = stress (pounds per sq. inch),

A = area (sq. inches),

P = load (pounds).

The total deformation is divided by the length of the specimen to obtain the unit deformation, inches per inch.

The points on the stress-strain diagram are simultaneous values of unit stress and unit strain computed from the recorded loads and the original dimensions (length and face area). The plotted points will not fall in line, but a straight line is drawn through the average area as represented by the points. Variations of points from the straight line are errors of the instruments and of observation. The multiplying lever deflectometer**, which was used for measuring deformation, is not a precision instrument. The plotted points, will, however, give an approximation of where the line should be, which is sufficiently accurate for the purpose of this investigation.

In an attempt to eliminate errors of observation the deflectometer was set at zero after a load of 1000 pounds had been applied to the specimen; therefore, if the complete deformation of the specimen is wanted, the curve should be extended past the point of zero deformation to the abscissa line. Adding this deformation to the total plotted deformation will give the total unit deformation of the specimen.

To illustrate the method of plotting, a typical stress-strain diagram is shown in Figure 1 on page 8.

** See page 19.

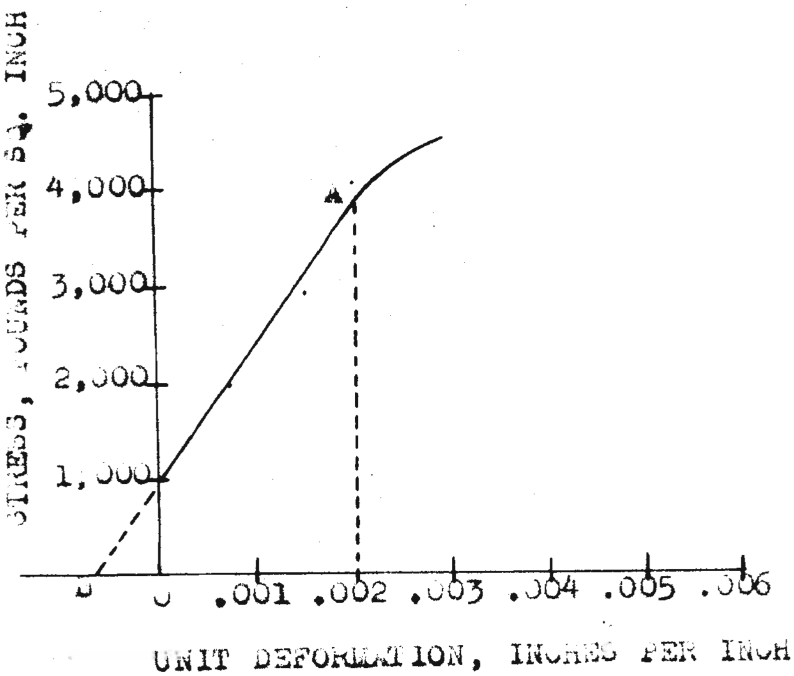

Figure 1. Typical Stress-strain Diagram.

This sketch shows how the curve starts at the point where the stress is 1000 pounds per square inch, or after the deflectometer is set at zero when the 1000 pound load is applied. To obtain the total deformation at point A, the curve drawn between the plotted points is extended to the abscissa line, point B, as shown by the dotted line. Scale the distance between 0 and B and add this distance to 0.002. The sum is the total unit deformation of the specimen at point A.

For most rocks, if the load is acting axially, the curve will be a straight line. This indicates that the unit stress and unit deformations are proportional; but when the elastic limit is reached the curve will swing from the straight line. The deviation from the curve indicates that the material is no longer conforming to Hooke's law.

Elastic Limit--Ultimate Strength--(E)

The elastic limit is considered to be at the same point as the proportional limit. The unit stress represented by the maximum ordinate on the stress-strain diagram is the ultimate strength. In addition to the ultimate strength, proportional limit, and elastic limit, the stress-strain diagram indicates the modulus of elasticity (E) of the material. This is the slope of the curve from the point of origin to the proportional limit; therefore, (E) is calculated from the following equation:

$$E = S/d; \qquad (2)$$

where

E = modulus of elasticity (pounds per sq. inch),

S = stress (pounds per sq. in.), at proportional limit

d = deformation (inch per inch) at proportional limit

In the stress-strain diagrams of rocks, which as tested in the laboratory are brittle materials, the rocks will rupture without warning. Brittle materials are not capable of much plastic deformation, and the stress-strain diagram will deviate gradually from the straight line.

Toughness

The area under the curve is a measure of the average work done per unit volume of the material. The modulus of elastic resilience is measured only by the area under the curve that is within the elastic limit.

The amount of energy per unit volume that a rock specimen stores when stressed to the elastic limit is called the modulus of resilience of that rock and is calculated from the following equation:[7]

$$U = Se^2/2E; \qquad (3)$$

where

7/ Laurson, P.G., and Cox, N.Y. Wiley, 1938 pp. 25 and 281

Johnson, J. B. 6th ed. N. Y. Wiley, 1925. pp. 38-42

U = modulus of resilience (in-lb. per cu. in.),

S_e = elastic limit (pounds per sq. in.),

E = modulus of elasticity (pounds per sq. in.).

Elastic toughness or resilience is an important mechanical property of a rock. Inasmuch as the modulus of resilience (U) is proportional to the square of the elastic limit and inversely proportional to E, a rock with a low elastic limit and a high modulus of elasticity would not be capable of absorbing a large energy load. Conversely, a rock with a high elastic limit and a low modulus of elasticity is capable of absorbing a high energy load. Comparison of the values of resilience for different rocks may give an indication of how each rock would act under confining pressures and quick impact shocks below the earth's surface.

The values obtained from the above formula should be checked against actual impact tests on the specimens; however, this method should give a classification order.

Transverse Tests[8/]

General

Transverse tests are used to determine the vertical shear, horizontal shear, and modulus of rupture of the material.

The three kinds of stresses-tension, compression, and shearing-- are developed when a beam is bent under the action of an external force. The lower portion of the beam or outermost fiber is under tensile stress,

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8/ Laurson, P. G. and Cox, N. Y. Wiley, 1938. pp. 101-140

Boyd, James E. 4th ed., N. Y. McGraw-Hill, 1935. pp. 19-44

Johnson, J. B. 6th ed., N. Y. Wiley, 1925. pp. 24-48

Winston, S. E. Chicago Am. Tech. Soc., 1944. pp. 19-44 the upper portion is under compression, and the point of maximum shear stress is at the neutral axis of the beam. Definitions and equations used in transverse tests follow:

Beam

A beam is a rock lying in a longitudinal position and being held up by two supports. Loads act at right angles to its length.

Static Equilibrium of a Beam

Static equilibrium in a beam requires that the sum of all forces acting on a beam in one direction must equal the sum of the forces acting in the opposite direction.

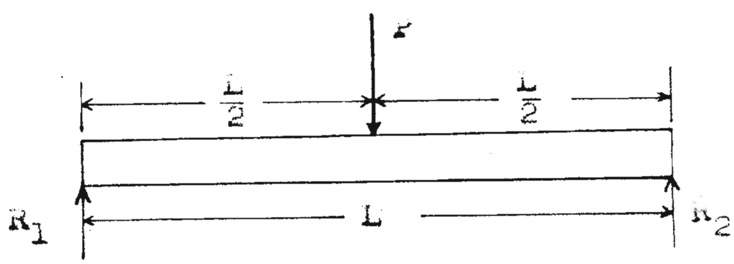

Figure 2. Simple Beam.

In Figure 2, the load P on the beam is the force acting in one direction, and P must be balanced by forces acting upward at the end reactions R_1 and R_2. In a simple beam loaded by a single concentrated load at the center of the span as in figure 2, $R_1 = P/2$ and $R_2 = P/2$.

Shear Stress

When a beam is loaded two kinds of shear stress acting at right angles to each other are developed. These are known as vertical and horizontal shear. The maximum shear stress in a rectangular section is $1\frac{1}{2}$ times the average shear stress.

Vertical Shear

Vertical shear at any section of a beam is calculated by the algebraic sum of the forces on the left side of the section. Forces acting downward are negative, and those acting upward are positive. To compute the vertical shear in a simple loaded beam with the load concentrated at the midpoint the shear diagram is used.

In Figure 3 there is shown a simple beam and the shear diagram. As in the former case the beam is in equilibrium and $R_1 = R_2 = P/2$

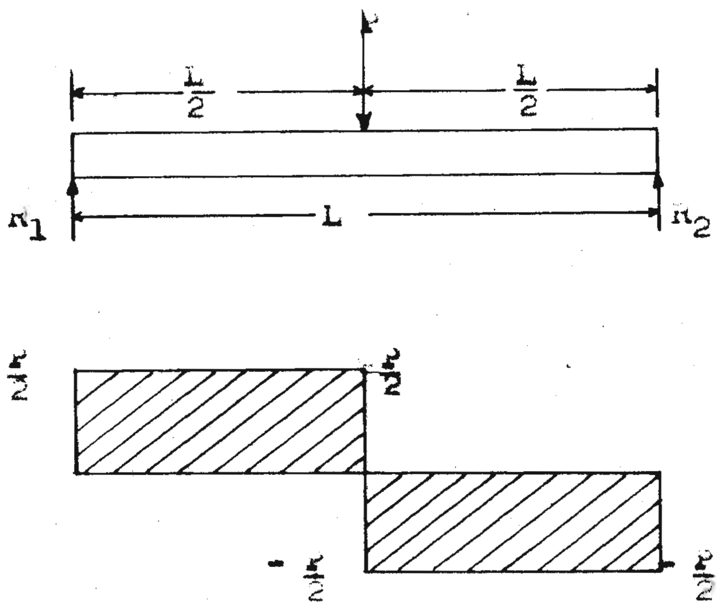

Figure 3. Shear Diagram.

At any section between the load and the left reaction the algebraic sum of the forces is the reaction R_1. The left segment moves upward with respect to the right segment. At the right of the load the vertical shear is the left reaction minus the load, which gives a minus shear equal to R_2. The maximum vertical shear (V) in this simple case of loading would be equal to either the right or left reaction or P/2.

Horizontal Shear

Horizontal shear develops at right angles to the vertical shear. Horizontal shear stress is the resistance of the tendency of one part of a beam on one side of a horizontal plane to slide by the part on the opposite side. In a rectangular beam the maximum horizontal shear is developed at the neutral axis of the section, or where there is no tension or compression in the beam.

The maximum shear stress in a rectangular beam is computed by the following equation:

$$H = 3V/2A; \qquad (4)$$

where

H = maximum shear stress (pounds) per square inch

V = maximum vertical shear (pounds),

A = Area of cross-section (inches^2).

Horizontal shear in below surface sedimentary rocks is an important theory in the formation of folds.[9/] Horizontal shear determination on a test specimen may not correspond to the action that takes place below the surface under large confining pressures, but a comparison of the action of rocks under shear in the laboratory may lead to the conclusion of what rocks will flow under acting stresses, and what rocks will shear under acting stresses. To apply this principle of horizontal shear it is necessary to consider folding as similar to the action of a beam. In the

9/ Forrester, J. D. N. Y. Wiley, 1946. pp. 17-19.

forming of an anticline, the axial plane would be the direction of the force, and the reactions would be at the axial planes of the adjoining synclines. (See Figure 4.)

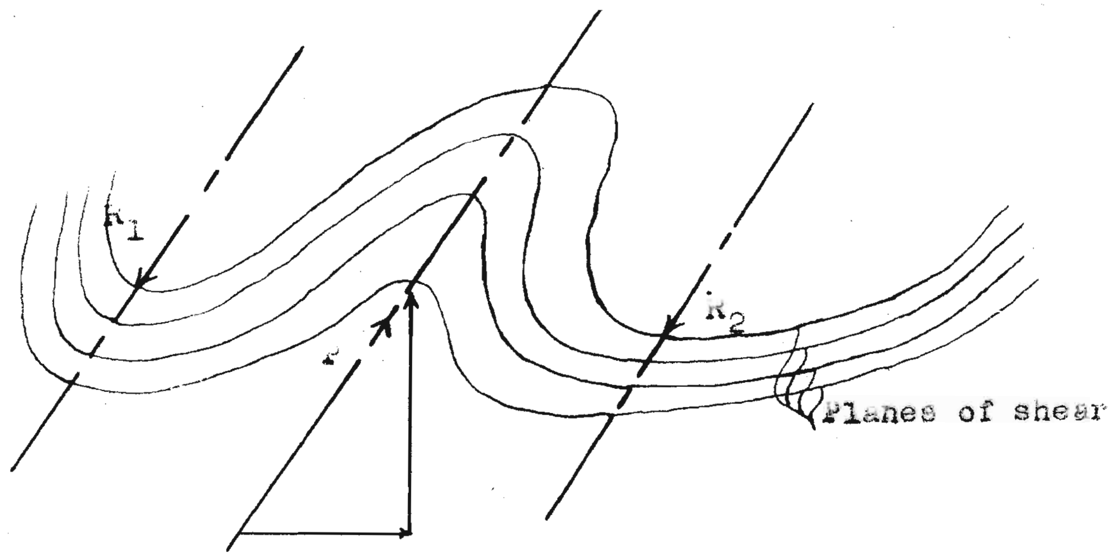

Figure 4. Anticline.

Maximum Bending Moment

The maximum bending moment is the greatest tendency of the external forces to cause rotation, and indicates the point where the beam is under the greatest horizontal test in bending. The bending moment is calculated by the algebraic sum of the moments either to the right or left of that section with respect to any point on that section.

Bending moments are for the effect of the load only.

The maximum bending moment equation for a beam with a single concentrated load at the center of the span is $\frac{PL}{4}$.

Modulus of Rupture

At every section of a beam there is a bending moment created by the forces to which the beam is subjected. The bending moment that has the largest value is the maximum bending moment and is designated with the symbol M.

The formula relating stress and bending moment for beams is:

$$M = SI/c; \tag{5}$$

where

M = maximum bending moment (in-lbs.),

S = stress (pounds per sq. in.),

I = moment of inertia (inches^4),

c = distance from the neutral axis to the outermost fibers (inches).

If a beam is loaded until failure occurs, and the maximum bending moment to which the beam was subjected is inserted in the above mentioned formula, the modulus of rupture (S_r) can be determined.

The modulus of rupture formula would be:

$$S_r = Mc/I \tag{6}$$

The ratio I/c of the formula is called the rectangular section modulus (Z). The section modulus for rectangular sections is $bh^2/6$, where b is the width and h is the height.

The modulus of rupture is not the unit stress in the outermost fiber of the beam at the moment of failure because the equation $S = M/Z$ is true only when the proportional limit has not been exceeded. The modulus of rupture is always greater than the actual tensile stress in the outermost fibers. In brittle materials, such as rocks, where the limit between the elastic limit and the breaking point is small, the modulus of rupture will closely approximate the unit tensile stress in the outermost fibers of the beam.

INSTRUMENTS AND MACHINERY USED IN TESTING

Specimen Preparation (sawing)

All specimens were prepared for testing by cutting them to uniform sizes with a Felker DI-Met cutting machine equipped with an 8 inch diameter DI-Met Rimlock* blade. This preparation of each specimen is a tedious chore, but it is one of the most important factors which govern the gathering of reliable test data.

A rock that is comparatively free from open joints and fractures should first be selected. It should then be broken by hammer and chisel to a size approximately 8" x 3" x 6". A rock of this size can be handled easily on the platform of the machine, and the cutting blade will make a primary cut through the specimen without further adjustment of the machine. The actual "cutting to size" operation can then be started. The following operating procedure should be pursued:

1. Cutting blades should be mounted on the machine so that their direction of rotation is in the direction of the arrow drawn on the blade.

2. The pressure on the cutting blade should be kept light and uniform, as forcing of the blade cuts down its speed of rotation and prematurely dulls the cutting edge. All new blades, though made by the same company, have a different cutting action. This difference ordinarily can be detected only after sawing has been done with each blade and, therefore, only after considerable time has been spent in specimen preparation.

3. During sawing, a constant flow of cold water should be kept applied at the point of contact where the blade engages the specimen.

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* Felker Manufacturing Company, Torrance, California

The use of oil as a coolant is not recommended.

4. Blades may be sharpened by making a few cuts through a sandstone.

5. A new blade must be used carefully. A lighter pressure than usual should be used until the blade starts to cut freely.

6. Blades that have been used for sawing several soft specimens usually cannot be used for cutting harder material, such as, porphyry, granite, and quartzite. The old blade should be removed and a new one mounted on the spindle to saw the harder material. The old blade can be kept and re-used when softer rocks are to be cut.

7. In cutting rocks containing minerals that differ widely in hardness, the blade will leave "saw grooves" along the cut surface. These grooves are unavoidable and do not need to be ground out except on the ends of the specimen.

8. The specimen should be measured carefully to keep a constant cross-section along its length. A small variation in cross-section will not seriously affect results, but a large variation should be corrected before testing is started.

9. When sawing the ends of the specimen, clamp a straightedge on the plate perpendicular to the blade. Select a side of the specimen that is relatively free from "saw grooves" and place this side against the clamped straightedge. Both ends of the specimen should be squared to the same selected side. Saw grooves on the ends of the specimen must be ground out.

<u>Specimen Preparation</u> (grinding)

The ends of the specimen were ground flat by carborundum dust.

The following procedure is recommended for the preparation of specimen ends.*

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* Dr. G. A. Muilenburg, personal conversation.

1. Select a piece of thick plate glass approximately 6" square.

2. Sprinkle carborundum dust on the glass and wet thoroughly.

3. Press the end of the specimen firmly against the dusted glass, and start a grinding motion describing a figure eight.

4. Flatness can be tested by occasionally washing off the grinding dust and placing the wet end of the specimen against the glass. If the specimen tends to stick to the glass, its end is flat.

Testing Machine

The testing machine is a 60,000 pound Tinius Olsen machine. Correct operation of this machine is important in obtaining good results. The Mechanics Department states in experiment (1a),

"Regardless of the type of testing machine, there are certain precautions which should be observed in its use in order to protect the machine and to insure that the test will give results which are representative of the material being considered. Some of these precautions are as follows:

(a) Do not start a machine into continued motion without first determining the speed and direction of the motion.
(b) Stop and start the machine with the controls provided for that purpose, not by some substitute means.
(c) Never try to reverse the direction of the driving motion or mechanism until all motion has stopped.
(d) Never leave a machine running unless an operator is at the controls.
(e) When a test is finished always leave the machine in "neutral" and with all switches open.
(f) Always see that the weighing device reads zero before any load is applied to the specimen.
(g) Center the specimen as carefully as possible so that the stress will be as nearly equivalent to the assumed kind as possible.
(h) Remember that the higher speeds of the testing machine are provided for the purpose of moving the parts of the machine in a minimum of time, and are not intended to be used in actual testing of materials.
(i) Remember that results of tests vary with methods of procedure, so that standard methods must be used if the results are to have any meaning when compared to other test data.
(j) Testing machines must be checked for accuracy from time to time. This may be done by weighing dead loads, using a

standard calibration bar, using calibration, levers, or using a proving ring.

(k) Testing machines must be checked for sensitiveness from time to time. This can be done by loading a specimen to various loads and determining what minimum weight placed on the machine will cause a readable movement of the weighing device. A weight of not more than $\frac{1}{250}$ of the load on the specimen should be discernible.

(l) The speed of the pulling head of the testing machine must be correlated with the settings of the controls so that the operator will know how rapidly the specimens are being deformed. This can be determined by timing the motion of pulling head for different settings of the controls."

By noting the marking on the valve control and by timing the amount of pounds applied per minute, it is possible to always keep the specimen loaded at the rate of 1000 pounds every 40 to 50 seconds.

Multiplying-lever Deflectometer[10/]

The deflectometer, which is an apparatus designed to measure the amount of any deformation that transpires before rupture, is calibrated to indicate deflections of 0.001 inch. By interpolation, deflections as small as 0.0005 inch can be determined.

The adjustable short arm of the deflectometer is placed against the head of the testing machine that is pressing on the end of the specimen. The deformation is read directly on the scale. The adjustable short arm allows setting of the deflectometer to zero at any load that is being applied by the machine. The procedure used in testing follows:

1. The specimen is centered exactly in the center of the swivel head of the testing machine.

2. A 1000-pound load is applied on the specimen.

3. The deflectometer is then set at zero by means of the adjustable short arm.

10/ Johnson, J. B. 6th ed., N. Y. Wiley, 1925. p 89.

4. Further deformation is read in inches from this starting load of zero deformation. For convenience in plotting, readings are taken as the load applied increases in 1000-pound increments.

EXPERIMENTAL COMPRESSION TESTS ON LIMESTONE

General

The experimental tests on limestone specimens were made to establish standardized test procedures that could be followed in testing of other rock types. The limestone was selected for these tests because of its homogeneous character, and because its ultimate strength is close to the average ultimate strength of all rocks. Tests standardized for limestone should be satisfactory for tests on the weaker rocks, such as shale and dolomite, and for stronger rocks, which include granites and porphyries. In addition to the need for a standardized laboratory testing procedure, the specimen length, and cross-section size, had to be determined.

Correlating laboratory data with actual field conditions will be difficult. Rock types vary within short distances, and jointing and fracturing is not the same in adjoining areas. Other geological factors that are variable over short distances are wall-rock alteration and metamorphism. These variable geological factors can be overcome by a proper geological interpretation of each area. The tests are made on a fresh rock; from this point the correlation of the laboratory data with field conditions must be made by a correct interpretation of the geological factors that would affect a fresh rock in the field.

Specimen Preparation and Testing

All specimens were cut parallel to the bedding planes of the rock. They ranged from 1.00 to 9.03 inches in length and from 0.808 to 1.07 square inches in cross-sectional area. The ends were squared off with the rock saw and not ground flat. Specimen lengths were measured to two decimal places and the cross-section area to three decimal places. The data sheet for each test is given in Appendix C.

The rate of loading in the testing machine was at 1,000 pounds every 40 to 50 seconds, and the adjustable swivel head was used on the compression machine.

Deformation readings were taken at 500-pound increments of loading after a 1,000-pound load had been applied to the specimen.

A stress-strain diagram has been plotted for each specimen from the data obtained.

Data Interpretation

Upon conclusion of the tests the assembled mass of data looked almost impossible to classify into any order; yet, there are several methods of classification. The first broad classification is the ultimate strength, which will divide the tests into two groups. When the specimen has reached its ultimate strength it explodes* at failure. The group that contains those specimens that failed to reach the ultimate strength can be classified further by the amount of deformation, angle of coning, and whether or not there was an apparent yield point**. All specimens that fail below the ultimate strength of the rock, thud*** at failure.

The specimens are grouped, according to the data determined, in Tables I, II, III, IV, V, AND VI. The explanation of each table follows:

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* Explosion—a sudden bursting with a loud report.

** Yield point is used here to define the point where the rock apparently fails by a longitudinal fracture, but the loading can be continued several thousand pounds past this point.

*** Thud—a dull sound produced by a fall on a soft substance.

Table I

The axially loaded rock specimens in Table I reached the ultimate strength of the rock and exploded at failure. The coning angle is 65°. The one inch cube showed no coning, and upon failure exploded into many fragments. The total unit deformation at the elastic limit ranged between 0.00233 inches and 0.00236 inches.

Table II

Near axially loaded specimens in this table ranged in ultimate strength from 9,530 to 11,050 pounds. The coning angle is 65°, and the sound at failure was partially explosive. The modulus of elasticity is variable, and the total unit deformation at the yield point ranged from 0.0005 to 0.00177 inches. There is an apparent yield point on all specimens.

Table III

Table III gives the specimens loaded on a sloping face. The specimens fractured at an angle of 65° back from the corner of the face. The modulus of elasticity, total unit deformation, and ultimate strength are variable, dependent upon how much of the specimen face the swivel head contacted during the test. There was no apparent yield point, and the sound at failure was a thud.

Table IV

This group had a coning angle greater than 65°, and their ultimate strength ranged from 7,100 to 8,540 pounds. Two of the specimens (17D and 17P) checked closely in total unit deformation at the yield point. The sound at failure was a thud.

Table V

All specimens in this group failed by longitudinal fracture. Examination of the fractures indicate a tendency toward bending in the specimen. The sound at failure was a thud and all the mechanical properties are variable.

Table VI

This group had a coning angle less than 65°. The ultimate strength ranges from 8,340 to 8,755 pounds. The modulus of elasticity and total unit deformation are variable.

On examination of these tests, it is immediately noticeable that a rock with an apparent yield point will not reach the ultimate strength of the material under any conditions of loading; further, there is a relationship between the angle of coning and the manner of loading. The sound at failure is also an important factor in determining that the specimen has been axially loaded. The total unit deformation at the apparent yield point of the rock is never as great as the total unit deformation at the elastic limit of a rock that reaches its ultimate strength and explodes upon failure.

The ultimate strength of a specimen is dependent on its length[11/] but large differences are not to be expected. A six-inch length specimen should give a strength not less than 0.82 of the ultimate strength of a cube; a 3-inch length specimen should give a strength not less than 0.84 of the ultimate strength of a cube. Later tests determine the reason for this ultimate strength and length relationship.

Specimens that were greater than 3 inches in length were difficult to keep at a constant cross-section throughout their length, and along with the compressive force being applied there also seemed to be a bending force. It is difficult to measure the deformation with a deflectometer on a specimen less than 2.5 inches in length.

11/ Johnson, J. B. 6th ed., N. Y. Wiley, 1925. pp. 112-116

The stress-strain diagrams (Plates I to VIII) give a clear picture of the action of each specimen under the compressive load. The explanation of each plate follows:

Plate I (test specimens 17S, 17T)

Test specimen (17S) is a perfect example of how a rock will deform under a compressive force. The deformation gradually increases, almost uniformly, as each additional 500-pound stress is applied. Somewhere near the load of 12,000 pounds per square inch and a unit deformation of 0.00232 inches, the curve swings over as the rock explodes and fails. The curve of test specimen (17T) is the action of a specimen near axially loaded and with an apparent yield point. Although the curve of (17T) parallels that of (17S) to the apparent yield point, there is no similarity beyond this point. The curve of (17T) swings almost horizontally after fracturing longitudinally and eventually fails with a thud, below the ultimate strength of the rock.

Plate II (test specimens 17Y, 17V, 17W)

The curve of the characteristics of specimen (17V) is an example of failure when the head of the machine is not flat upon the face of the rock. The unit stress at failure is far below the ultimate strength. Curves of specimens (17Y and 17W) are examples of those failing by longitudinal fracture.

Plate III (test specimens 17J, 17N, and 17I)

The curve of specimen (17N) corresponds closely to that of (17T) Plate I, and (17J) resembles (17V) of plate II. Specimen (17I) fractured longitudinally with an apparent yield point of 3,800 pounds per square inch.

Plate IV (test specimen 17H, 17X, 17G)

The diagram of the characteristics of specimen (17H) is another example of a curve where the rock has reached its ultimate strength and failed suddenly by an explosion. Specimens (17X and 17G) are from the group of tests that coned at less than 65°. They have no apparent yield point, but the strength does not approach that of specimens (17H).

Plate V (test specimen 170 and 17R)

The curve of specimen (17R) is similar to the curve of (17T) of Plate I and (17N) of Plate III. Test speciment number (170) fractured longitudinally at the 2700 pound per square inch point, but seemed to recover and hold the deformation at a steady constant increase from that point onward.

Plate VI, VII AND VIII

The curves shown on these plates are similar to the ones shown on Plates I to V. Classification into groups usually classifies the curve.

Many specimens after fracturing longitudinally continued to stand additional loads. This caused a shearing action on the plane of the fracture. Small fragments were ground off from the outside of the specimen at the plane of the break, and powdered rock was noticeable after the specimen had failed.

The coning angle, which has been used as a classification into groups, is not developed by shearing. The angle is measured from the horizontal, and the plane of break is a parting plane or better, a tearing plane. Near the point of the cone a small shearing action can be noted, but this shear includes only the point of the cone. The rest of the plane is a clean break. See Figure 5.

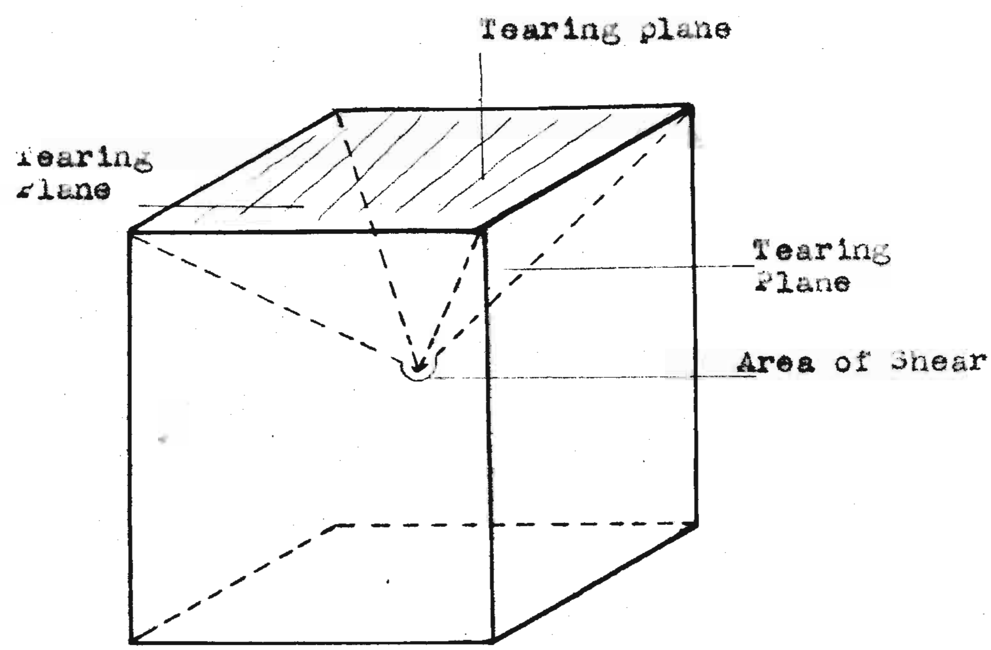


Figure 5. Coning Angle.

The term "coning angle" does not necessarily mean that the specimen coned, but instead, means that there was an angle of parting in place of a straight longitudinal fracture through the length of the specimen. Those specimens that were not square developed a wedge-shaped fragment upon failure.

TABLE I. LIMESTONE SPECIMENS LOADED AXIALLY

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent yield point lb/sq.in.	Deformation at y.p.	Coning Angle	Remarks
17	1.00	1.000	14,780	----------	-----------	-----------	fragments	Explosion
17S	3.00	0.814	13,390	5.10×10^6	-----------	0.00	65°	"
17H	6.97	1.026	12,915	4.9×10^6	-----------	-----------	65°	"

TABLE II. LIMESTONE SPECIMENS LOADED NEAR AXIALLY

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent yield point lb/sq.in.	Deformation at Y.P.	Coning Angle	Remarks
17T	3.02	0.808	9,530	4.2×10^6	7,425	.00177	65^o	Explosion
17A	2.98	1.035	10,050	5.8×10^6	8,700	0.00149	65^o	Explosion
17R	2.95	1.029	10,010	3.8×10^6	1,945	.00051	65^o	Explosion
17N	3.02	1.041	11,050	4.14×10^6	6,240	0.00144	65^o	Explosion

TABLE III. LIMESTONE SPECIMENS LOADED ON A SLOPING FACE

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent Yield Point lb/sq.in.	Deformation at Y. P.	Coning Angle	Remarks
17U	4.04	0.876	2,400	---------	----------	----------	65°	Thud
17V	6.07	0.899	5,670	6.80×10^{6}	----------	----------	65°	Thud
17J	9.03	0.975	7,180	4.9×10^{6}	----------	----------	65°	Thud

TABLE IV. LIMESTONE SPECIMENS THAT CONED GREATER THAN 65°

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent Yield Point lb/sq.in.	Deformation at Y.P.	Coning Angle	Remarks
170	3.07	0.925	8,540	4.37×10^6	-----------	-----------	70°	Thud
17D	3.00	1.042	7,100	3.14×10^6	6240	0.00148	67°	Thud
17P	3.05	0.912	7,455	3.26×10^6	4935	0.00142	85°	Thud

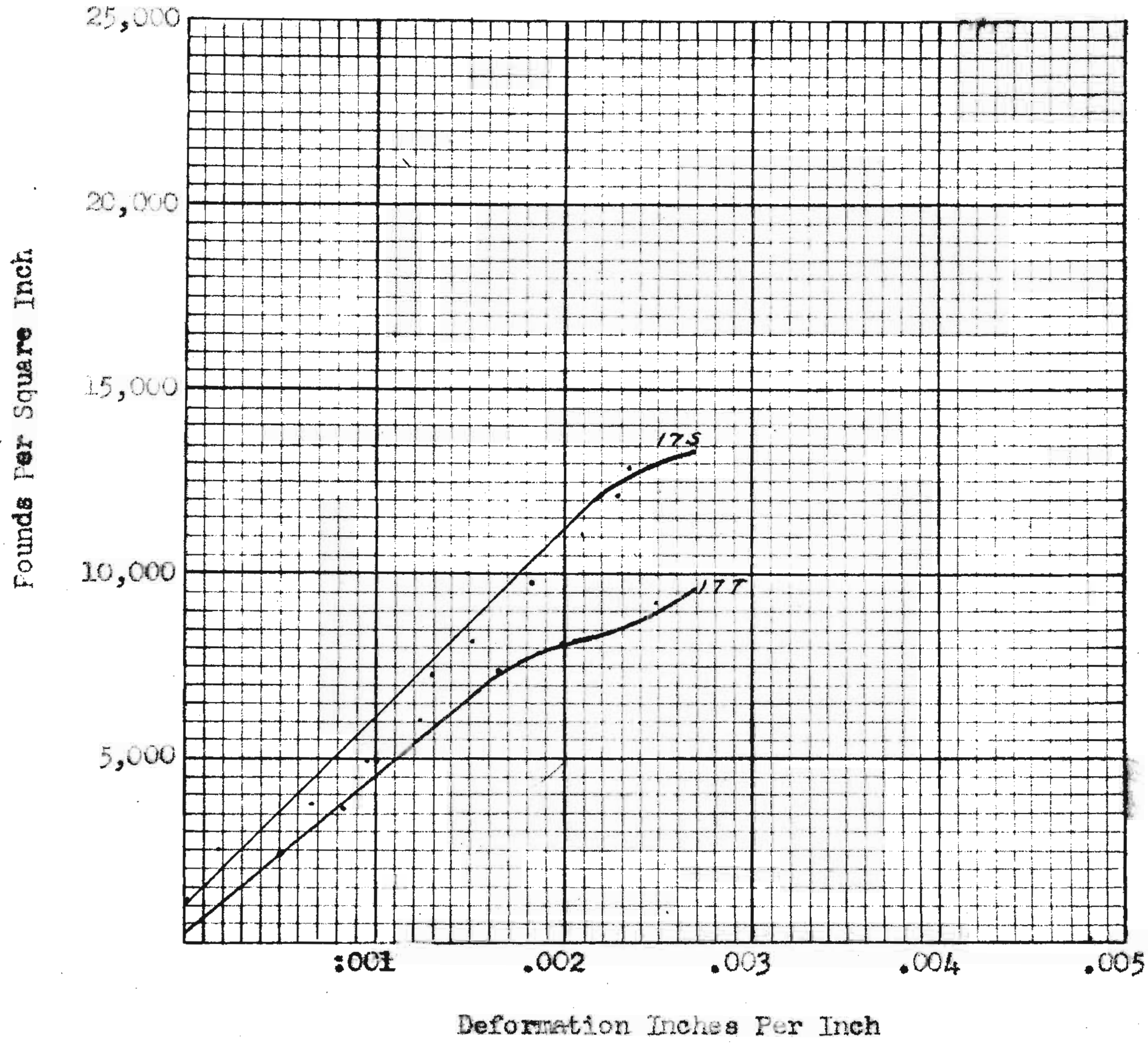
TABLE V. LIMESTONE SPECIMENS THAT FRACTURED LONGITUDINALLY

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent Yield Point lb/sq.in.	Deformation at Y. P.	Coning Angle	Remarks
17B	2.00	1.018	6,680	2.00×10^6	5,790	0.00225	------	Thud
17C	2.01	0.960	8,640	4.58×10^5	7,810	-------	------	Thud
17K	3.57	0.917	5,560	5.2×10^6	3,815	.00073	------	Thud
17M	5.02	0.890	5,710	3.53×10^6	4,720	0.00117	------	Thud
17W	7.10	0.873	7,905	8.2×10^6	4,580	0.00065	------	Thud
17I	8.03	1.076	5,020	2.82×10^6	3,800	0.00125	------	Thud
17Y	8.09	0.928	9,590	9.7×10^6	8,620	0.00089	------	Thud

TABLE VI. LIMESTONE SPECIMENS THAT CONED LESS THAN 65°

Test #	Length inches	Area inches	Ultimate Strength lb/sq.in.	E lb/sq.in.	Apparent Yield Point lb./sq.in.	Deformation at Y.P.	Coning Angle	Remarks
17Q	3.03	0.811	8.755	3.8×10^6	-----------	0.00163	60°	Thud
17E	3.92	1.033	8,620	2.95×10^6	-----------	0.0018	61°	Thud
17X	4.98	1.031	8,340	4.98×10^6	-----------	0.00128	60°	Thud
17G	6.00	1.069	8,510	5.55×10^6	-----------	0.00120	60°	Thud

PLATE I, STRESS-STRAIN DIAGRAM, LIMESTONE (17S, 17T) //

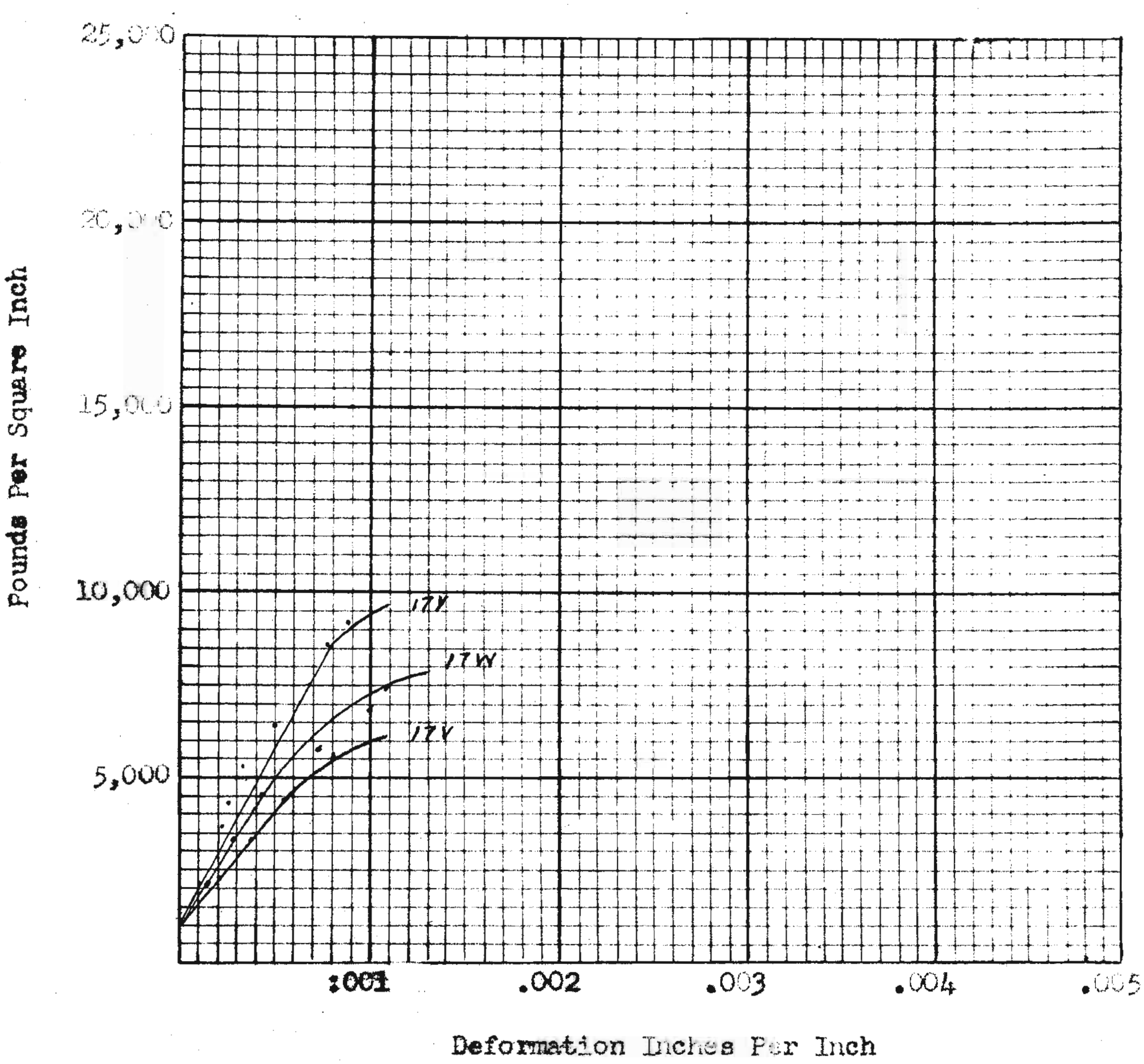


(17S) Elastic Limit = 12,000 Pounds Per Square Inch

(17S) Modulus of Elasticity = 5.1×10^6 Pounds Per Square Inch

(17S) Modulus of Resilience = 14 Inch-Pounds Per Cubic Inch

PLATE II, STRESS-STRAIN DIAGRAM, LIMESTONE (17Y, 17W, 17V) //

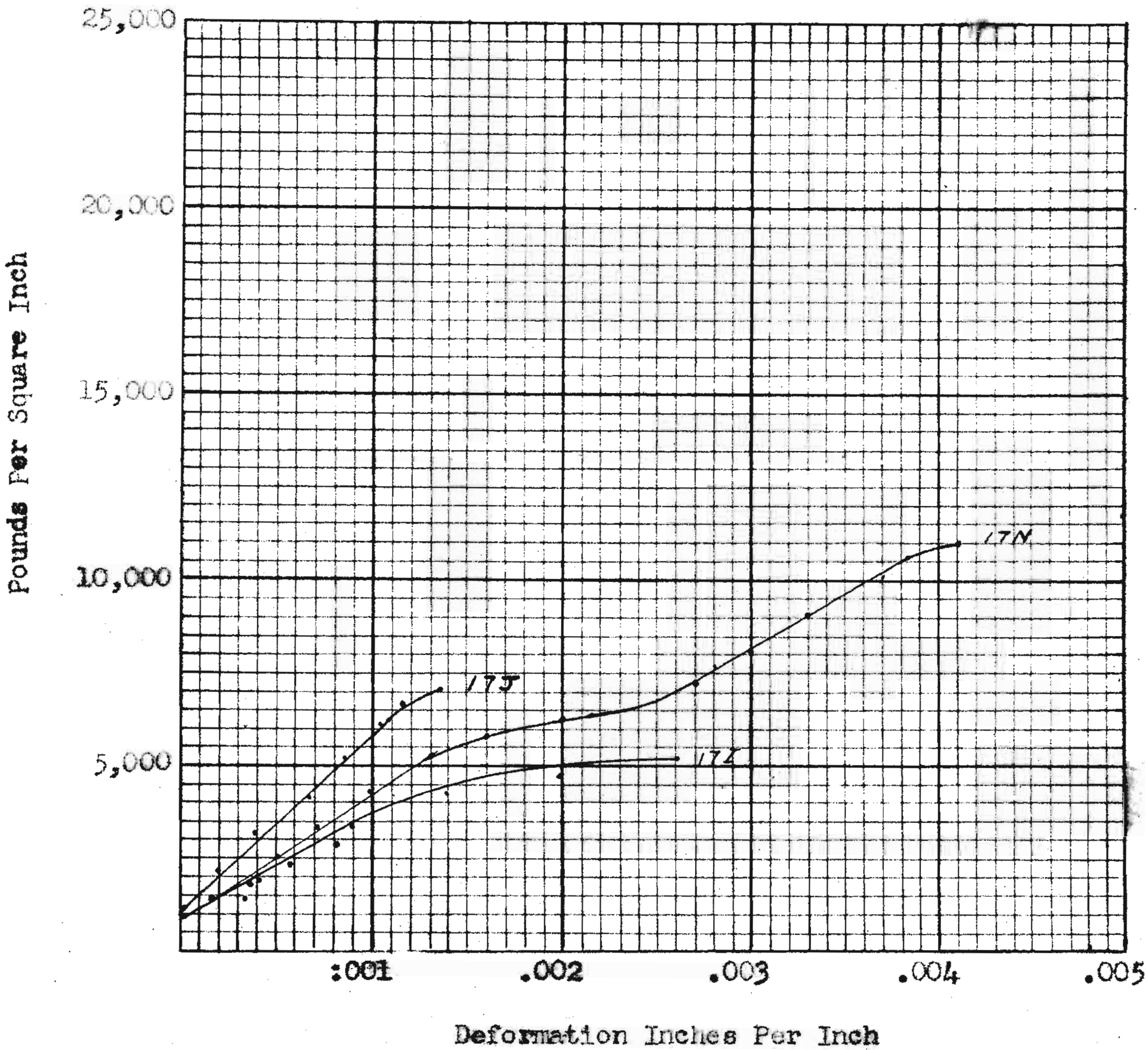


(17V) Elastic Limit = 4,450 Pounds Per Square Inch

(17V) Modulus of Elasticity = 6.8×10^{6} Pounds Per Square Inch

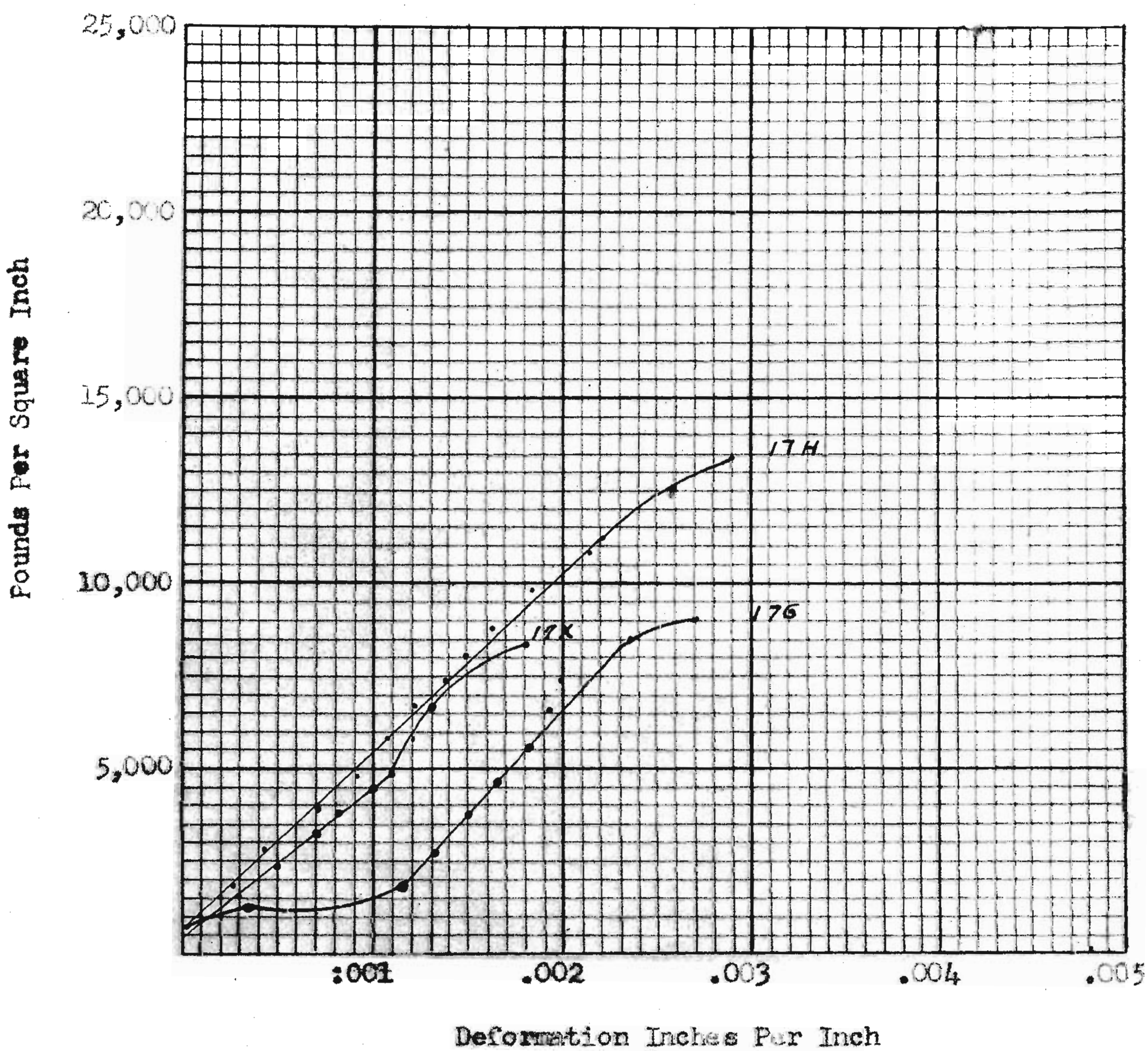
(17V) Modulus of Resilience = 2 Inch-Pounds Per Cubic Inch

PLATE III, STRESS-STRAIN DIAGRAM, LIMESTONE (17J, 17N, 17I) //



(17J)	Elastic Limit =	6155	Pounds Per Square Inch
17J	Modulus of Elasticity =	4.9×10^6	Pounds Per Square Inch
17J	Modulus of Resilience =	4	Inch-Pounds Per Cubic Inch

PLATE IV, STRESS-STRAIN DIAGRAM, LIMESTONE (17H, 17X, 17G)

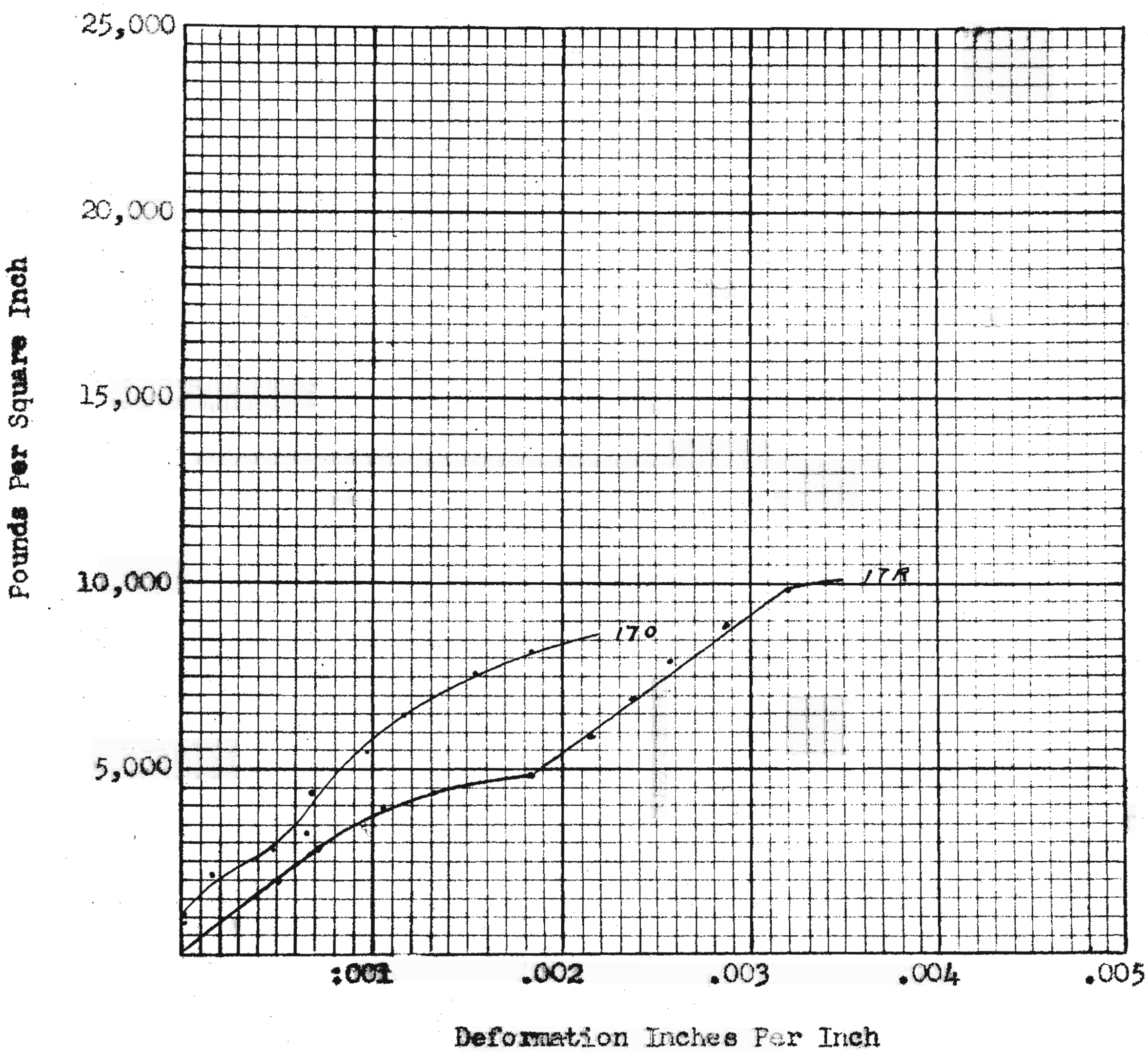


(17H) Elastic Limit = 11,210 Pounds Per Square Inch

(17H) Modulus of Elasticity = 4.9×10^6 Pounds Per Square Inch

(17H) Modulus of Resilience = 13 Inch-Pounds Per Cubic Inch

PLATE V, STRESS-STRAIN DIAGRAM, LIMESTONE (17O, 17R) //

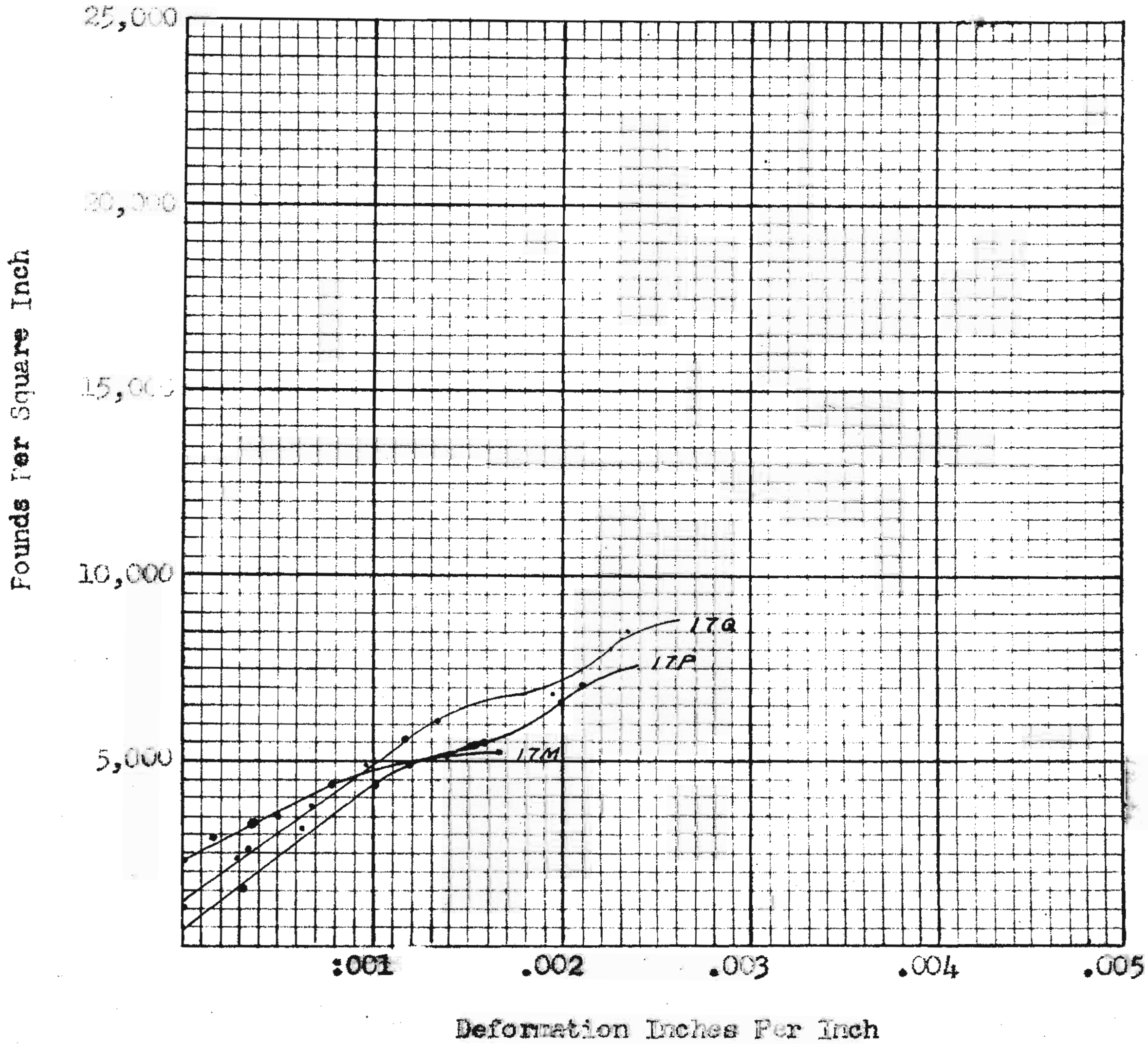


(17R) Elastic Limit = 1945 Pounds Per Square Inch

(17R) Modulus of Elasticity = 3.8×10^6 Pounds Per Square Inch

(17R) Modulus of Resilience = .5 Inch-Pounds Per Cubic Inch

PLATE VI, STRESS-STRAIN DIAGRAM, LIMESTONE (17Q, 17P, 17M) //

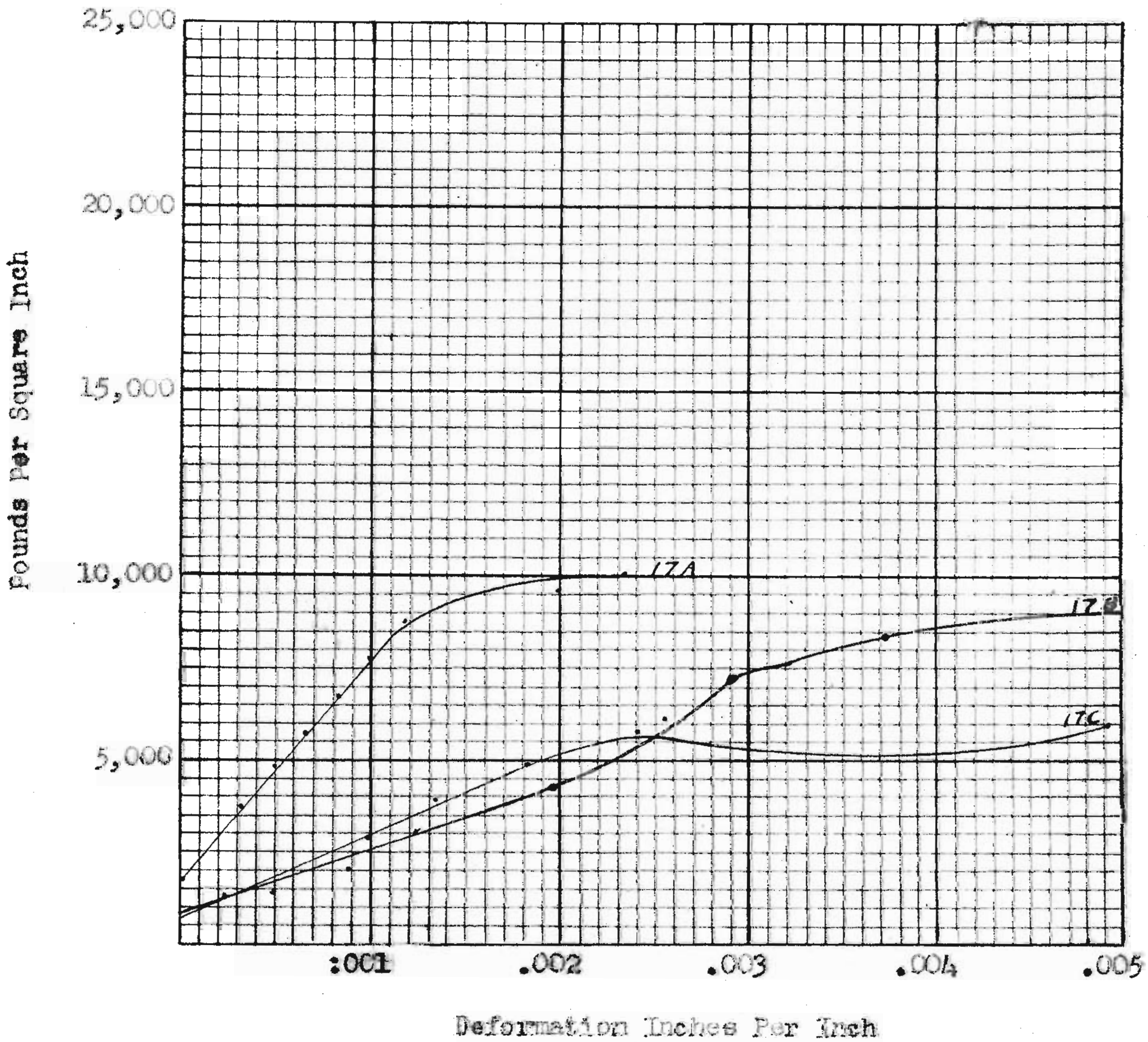


(17Q) Elastic Limit = 6,165 Pounds Per Square Inch

(17Q) Modulus of Elasticity = 3.8×10^6 Pounds Per Square Inch

(17Q) Modulus of Resilience = 0.4 Inch-Pounds Per Cubic Inch

PLATE VII, STRESS-STRAIN DIAGRAM, LIMESTONE (17A, 17B, 17C)

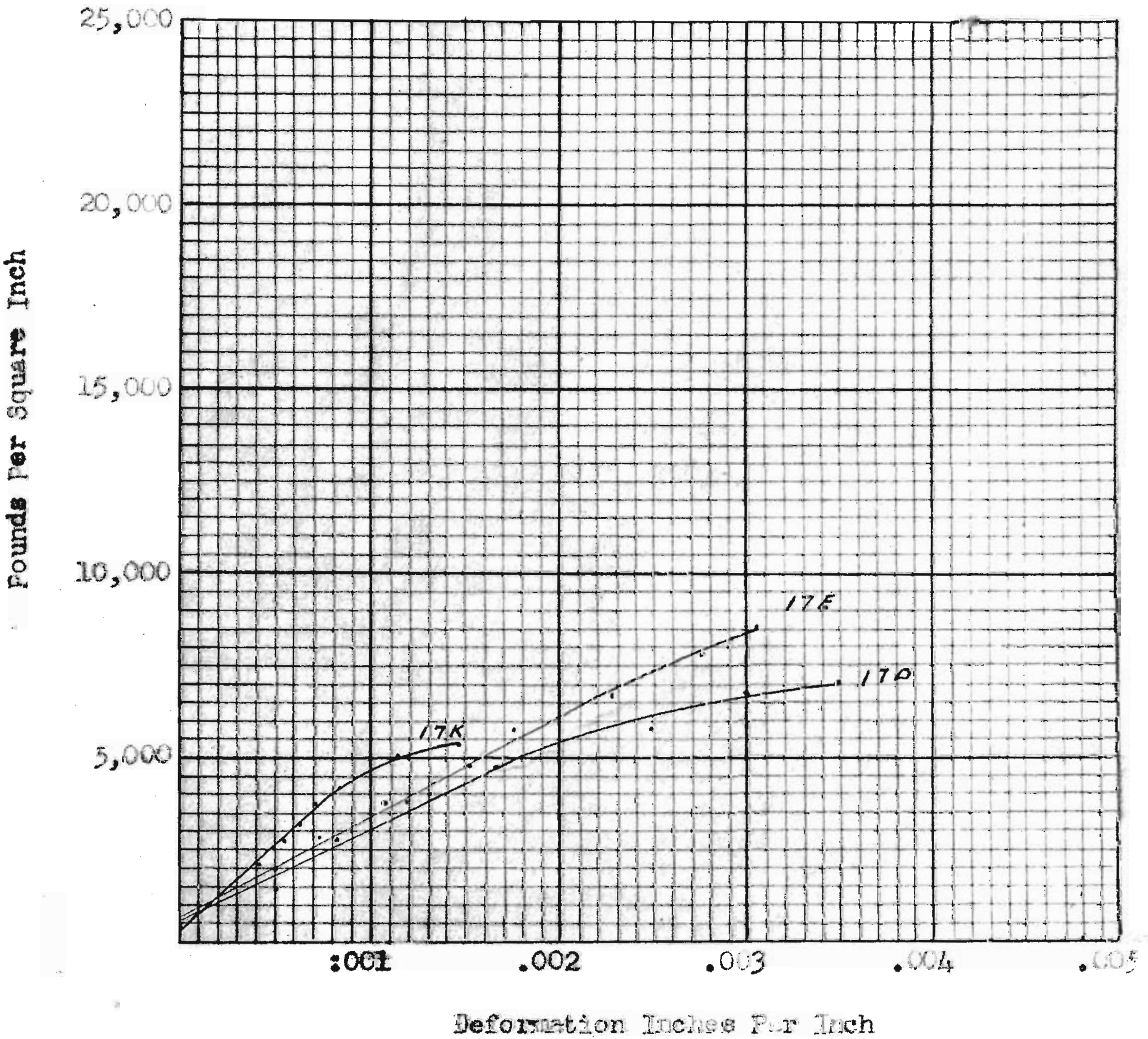


(17A) Elastic Limit = 8700 Pounds Per Square Inch

(17A) Modulus of Elasticity = 5.8×10^6 Pounds Per Square Inch

(17A) Modulus of Resilience = 7 Inch-Pounds Per Cubic Inch

PLATE VIII, STRESS-STRAIN DIAGRAM, LIMESTONE (17K, 17E, 17D)



(17K) Elastic Limit = 3815 Pounds Per Square Inch

(17K) Modulus of Elasticity = 5.2×10^6 Pounds Per Square Inch

(17K) Modulus of Resilience = 1 Inch-Pounds Per Cubic Inch

Summary

From the results of the foregoing experimental compressional tests conducted specimens of limestone the following controlling factors have been ascertained:

1. A test specimen should measure about 1" x 1" x 3". Specimens less than 2.5 inches long are unsatisfactory.

2. The ends of the specimen should be ground flat.

3. A fresh specimen, comparatively free from joints and fractures, should be cut from the original rock sample.

4. Deformation readings taken at 1000-pound increments will be satisfactory for plotting the stress-strain diagrams.

5. All recorded data should be corrected by Formula 1.

6. The angle of coning, the character of the explosion at rupture, and the shape of the fragments should be noted on the data sheet.

7. A test specimen that has no apparent yield point and which explodes at rupture should be plotted on a stress-strain diagram.

8. If the curve on the stress-strain diagram plots uniformly, that is, with a steadily increasing deformation at each 1000-pound increase in stress, and showing a small increment of deformation between the deformation at the elastic limit and the deformation at the ultimate strength, the specimen has reached the ultimate breaking strength.

9. If a specimen explodes at rupture and plots as a uniform curve on a stress-strain diagram as noted in (8) above, that is the only specimen of that rock that needs to be tested.

10. The modulus of elasticity (E) will be computed by Formula 2.

11. The coning angle is not produced by shear.

MODULUS OF RUPTURE TESTS

General

These Transverse tests were made to determine the approximate strength of a rock in tension, and also the horizontal and vertical shear produced by the force at failure of the specimen.

Two specimens for each rock type were prepared. One for testing with the force acting parallel to the bedding planes, and the other for study when the force was acting perpendicular to the stratification. Different lengths were prepared and tested with the support and bearing device as sketched in Figure 6. The side of the specimen that rested on the supports was ground flat. The results of the investigation are listed in Table VII.

Data Interpretation

The results of these tests are not conclusive. The objective of the tests was to find the approximate strength of the rock type in tension, and also to determine if a rock could be made to shear by this manner of testing.

A sedimentary rock that has pronounced bedding planes will fail along these bedding planes when the force is applied parallel. The results in Table VII would probably be more uniform if the force had been applied on all specimens perpendicular to the bedding planes. In all tests a ½-inch overlap beyond the supports was allowed.

As stated on page 15, the formula ($S = M/Z$) is not the stress in the outermost fiber of the beam at the moment of failure; because the equation is true only when the proportional limit has not been exceeded. However, the modulus of rupture should closely approximate the strength of the rock in tension.

The specimens all failed in tension on the outermost fiber regardless of the length of the beam.

Summary

The results of the modulus of rupture tests are not conclusive, and more experimental work must be done to standardize the testing procedure. Conclusions based on the data of the foregoing tests would indicate:

1. The force should be applied perpendicular to the bedding planes of the rocks.

2. The size of satisfactory test specimen is 1" x 1" x 5". This will give 4 inches between supports with a one-half inch overlap beyond the support on each end.

3. The side of the specimen that rests on the supports should be ground flat.

4. A test specimen should be taken from a portion of the sample that is relatively free from fractures.

5. The modulus of rupture of a rock may be computed by formula 6.

6. The maximum shear stress need not be computed.

7. The results may be tabulated in the form of Table VII.

8. For investigations based on determining the mechanical properties of rocks by petrographic analysis, the modulus of rupture may be used as the ultimate strength of the rock in tension.

9. The support and bearing device as drawn in Figure 7 should be used for all tests.

TABLE VII. MODULUS OF RUPTURE TESTS

Rock Type	Size Inches	Length Inches	Force (P) lbs.	Area Sq.In.	S_r lb/sq.in.	Maximum Shear Stress lb./sq.in.
Limestone ⊥	b 1.02 h 1.00	4	470	1.02	2,760	346
//	b 1.00 h 1.00	2	760	1.00	2,280	570
Sandstone ⊥	b 1.00 h 1.02	2	335	1.02	960	247
//	b 0.96 h 1.00	2	175	0.96	550	333
Shale ⊥	b 0.84 h 0.98	4	565	0.82	4,220	516
//	b 0.94 h 1.00	1	615	0.94	1,000	492
Granite	b 0.96 h 0.94	3	375	0.90	1,980	322
Dolomite ⊥	b 0.98 h 1.00	4	200	0.98	1,220	153
//	b 0.96 h 0.96	3	265	0.92	1,350	217
Conglomerate ⊥	b 1.02 h 0.98	3	290	1.00	1,330	218
//	b 0.98 h 0.98	1	2,100	0.96	3,340	1,640
Porphyry	b 0.98 h 0.96	4	750	0.94	4,950	598

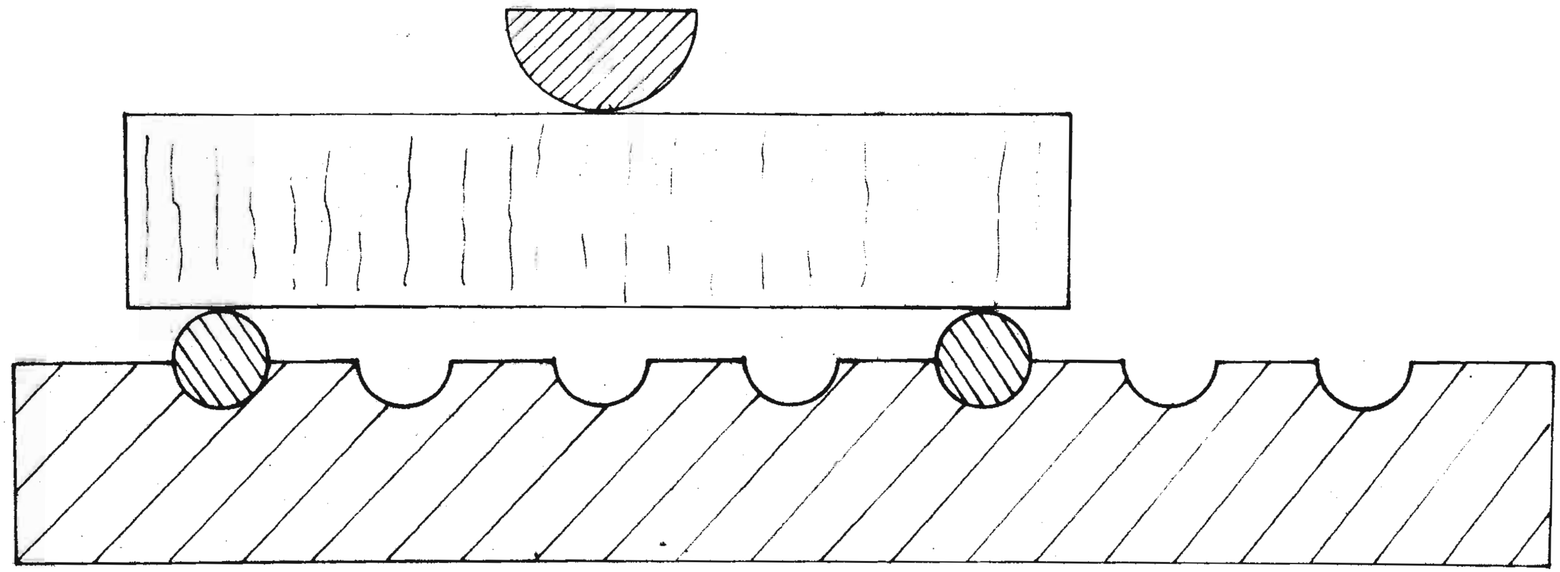


Figure 6, Support and bearing for modulus of rupture test

EXPERIMENTAL COMPRESSION TESTS ON ROCK TYPES

General

The purpose of the tests, which were made of several rock types, is to verify the original tests made on the limestone used for developing standard procedure; to determine the relative strengths of any rock when a load is applied either parallel or perpendicular to the bedding planes; to ascertain the reason for the coning angle and its character; and to analyze the manner in which the rock fails at rupture. The rock types which were tested were selected so as to represent as nearly as possible a general average of characteristics of all rocks that eventually will be encountered in any investigation concerned with determining the mechanical properties or rocks.

Specimen Preparation and Testing

The six rock types selected for the tests are as follow: limestone, sandstone, shale, granite, dolomite, and conglomerate. The length of many of the specimens is below the recommended 3 inches, but the small size of the original samples from which the specimens were cut made it impossible to obtain longer units.

Two sets of test specimens were prepared; one set was cut so that the length was parallel to the bedding planes where such planes are present; the others perpendicular to the bedding planes. The ends of all specimens were ground flat. The data sheet for each test is given in Appendix C.

The rate of loading in the testing machine was at 1,000 pounds every 40 to 50 seconds, and the adjustable swivel head was used on the compression machine.

Deformation readings were taken in 1,000-pound increments after a 1,000-pound load had been applied to the specimen.

Data Interpretation

Table VIII is a tabulation of the experimental data obtained from the tests of the six rock types. Plates IX to XVII are the stress-strain diagrams of selected specimens from each group.

A stress-strain diagram has been plotted for one specimen of each set. The explanation of each stress-strain diagram follows:

Plate IX and X

Plate IX is a diagram of the characteristics of limestone when tested with the load perpendicular to the bedding planes, and Plate X is a curve of the same rock when the load was acting parallel to the bedding planes. The ultimate stress depicted and slope of the curves of both diagrams are almost identical. Any one of the specimens of the limestone group that exploded at failure could have been used for the diagram and for the computation of the modulus of elasticity. The question may be raised as to why the average of all tests of the specimens was not taken and why that average was not used in determining the ultimate strength of the limestone. An analysis of the stress-strain diagram will answer this question. The modulus of elasticity is the slope of the line up to the elastic limit and is an approximate average, the accuracy depending alone upon where the line has been located with reference to the plotted points. In locating the line, differences of opinion may result in different values for the modulus of elasticity and elastic limit, but the values would not differ greatly. In addition, in locating the line the stress per square inch and the deformation are averaged simultaneously. The proper location of the line rests upon the judgment of the investigator, and a study of the stress-strain diagrams of different materials[12/] will aid in locating the

12/ Boyd, James E. 4th ed., N. Y., McGraw-Hill, 1935 pp. 39-104 line.

Plate XI and XII

Plate XI is a curve of tests of weathered sandstone which was loaded perpendicular to the bedding planes, and XII is a curve developed when fresh sandstone was loaded parallel to the bedding plane. The strength and modulus of elasticity of a weathered rock is not as great as that of a fresh specimen of the same material. The weathered specimens check closely in strength (see Table VIII) when loaded either parallel or perpendicular to the bedding planes. The ultimate stress of a weathered specimen would, of course, vary with the amount of alteration that the rock had undergone.

Plate XIII

Plate XIII is stress-strain diagram of the characteristics of shale which was stressed parallel to the bedding planes. Specimens 22FF and 22GG, which were loaded perpendicular to the bedding planes, check with the ultimate strength that was obtained from parallel loading.

Plate XIV

This is a diagram of the characteristics shown by a granite that failed with an explosion at 16,180 pounds per square inch. It represents the results obtained from the first test which was made of an igneous rock. The action of the specimen under a compressive stress apparently is no different in principle than that of the limestone. For example, a comparison with Plate X will show the same general properties, namely; a definite deformation as each 1,000-pound increment of stress is applied, and a small interval between the elastic limit and the breaking point. The fact that a parallelism exists between tests of the igneous rock and of the limestone is, of course, expected and reasonable.

Plate XV

This diagram depicts the reaction of dolomite when stressed parallel to the bedding plane. Those specimens of the dolomite loaded perpendicular to the bedding parted on the chert stringers. The ultimate strength of this rock therefore, must be determined with the load acting parallel to the bedding planes.

Plate XVI and XVII

Plate XVI and XVII are the diagrams of the failure of conglomerate when loaded parallel and perpendicular, respectively, to the bedding planes. They are essentially similar in all respects though variable results are often obtained on different test specimens of a rock of this type inasmuch as differential strain fragments of harder materials within the conglomerate seem to build up differential strain. Thus, whenever a test specimen contains a preponderance of harder pebbles than that contained in another specimen from the same rock it may fail with an explosion at a considerably lower range than would the latter specimen. The variation between specimens may be as great as 17 percent. Therefore, several specimens of this rock type have been tested to make certain that the ultimate strength has been reasonably determined.

Summary

From the results of the foregoing experimental compressional tests conducted on specimens of several rock types by a standardized test procedure, the following factors have been ascertained:

1. Most sedimentary rocks may be tested satisfactorily by stresses acting either parallel or perpendicular, respectively, to the bedding planes. The final results are basically the same.

2. Those sedimentary rocks having stringers of "foreign material" that disrupt their general homogeniety on the bedding planes should be

tested with the force acting perpendicular to the bedding planes.

3. Several specimens of a conglomerate type rock should be tested to make certain that the ultimate strength has been ascertained. This is particularly true if the constituent pebbles are comparatively large and not uniformly distributed through the rock.

4. Igneous rocks should be tested by the same methods as those used for studying the failure of sedimentary rocks.

5. If a fresh rock specimen is tested it will give indication of higher ultimate strength than will a weathered specimen of the same type.

6. When a rock being stressed fails along some hidden fracture or bedding plane, the sound at failure is a thud, and the ultimate strength of the material in general will not have been demonstrated.

7. The modulus of resilience of a rock may be computed by using formula 3; the elastic limit may be estimated from the relations shown by the stress-strain diagram which results from the test of each rock type.

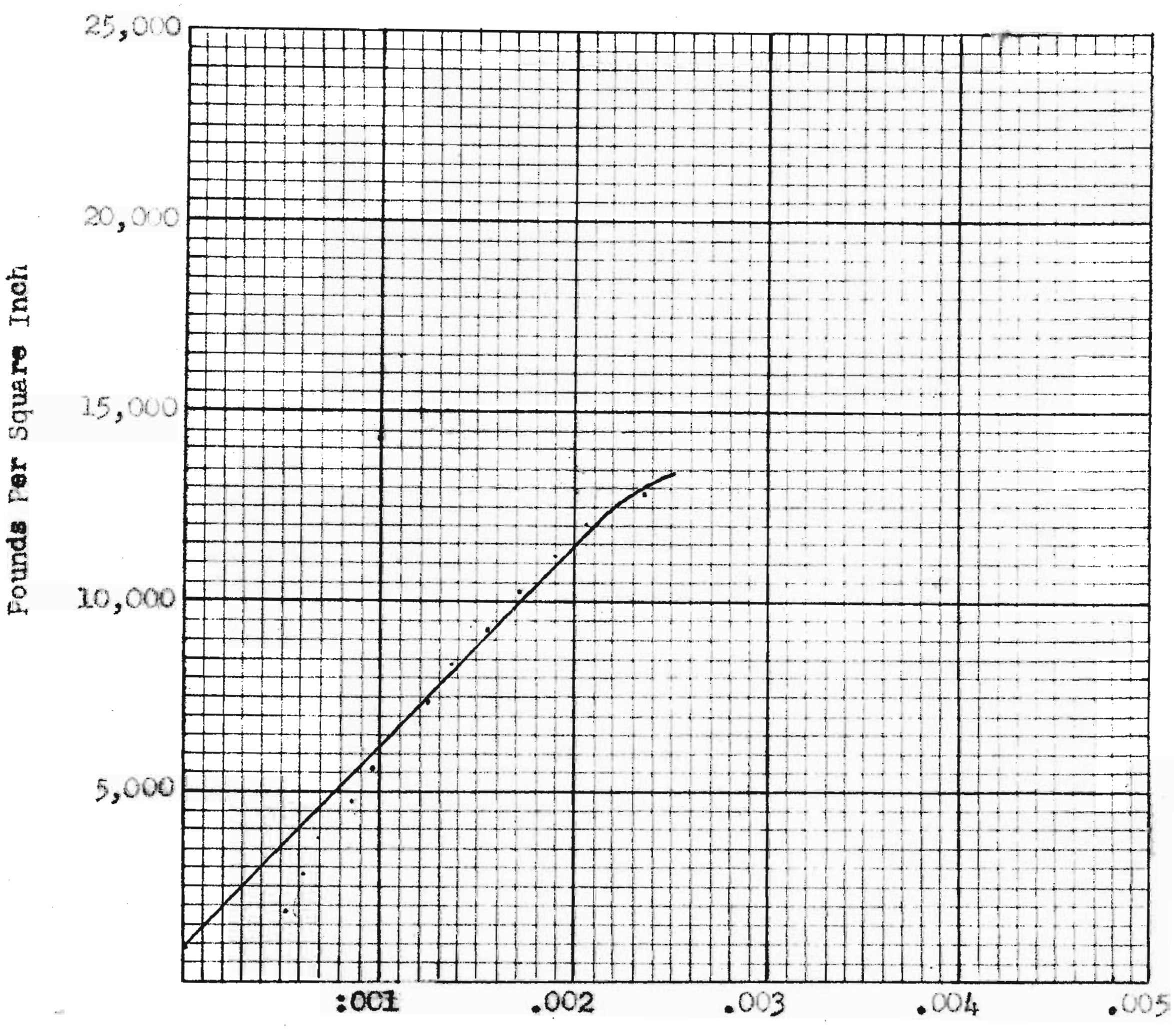
TABLE VIII. COMPRESSIVE STRENGTH OF ROCK TYPES

Rock & Direction of Loading		Length Inches	Area Sq.In.	Ultimate Stress lb/sq.in.	Remarks
Limestone	17S //	3.00	0.814	13,390	Explosion (Plate X)
	17AA ⊥	2.90	1.010	14,000	Explosion
	17BB ⊥	2.92	1.000	13,450	"
	17CC ⊥	2.89	1.030	6,400	Thud
	17DD ⊥	2.88	1.010	6.600	"
	17EE ⊥	2.90	1.010	6,640	"
	17FF ⊥	2.90	1.008	13,000	Explosion
	17GG ⊥	2.93	1.040	13,720	"
	17HH ⊥	2.87	1.080	13,700	" (Plate IX)
Sandstone	11A //	3.00	0.990	10,810	Explosion
	11B //	2.87	1.060	7,260	Thud (weathered)
	11C //	2.14	0.940	12,680	Explosion (Plate XII)
	11D //	2.40	0.980	8,060	Explosion (weathered)
	11AA ⊥	2.52	1.000	8,200	Explosion (partiall weathered)
	11BB ⊥	2.35	0.990	6,960	Thud
	11CC ⊥	2.36	0.985	7,340	Thud
	11DD ⊥	2.38	0.950	8,360	Explosion (weathered) (Plate XI)
Shale	22F //	3.09	0.940	9,255	Explosion
	22G //	2.92	0.970	10,410	Explosion (bottom polished) (Plate XIII)
	22I //	3.06	0.610	10,163	Explosion
	22BB ⊥	1.14	1.000	11,450	Explosion (Ends oiled with light oil.)

(TABLE VIII CONTINUED)

Rock & Direction of Loading		Length Inches	Area Sq.In.	Ultimate Stress lb/sq.in.	Remarks
Shale	22CC ⊥	1.40	1.000	9,000	Explosion. (Ends greased)
	22FF ⊥	1.03	1.020	12,250	Explosion
	22GG ⊥	1.00	0.980	13,490	"
Granite	23A	3.00	0.970	15,060	Explosion
	23B	3.03	0.970	16,180	" (Plate XIV)
	23C	2.95	0.960	13,800	" (polished bottom)
	23D	0.90	1.000	23,150	Explosion
	23X	4.00	1.020	11,760	Explosion (greased ends)
	23Y	4.00	1.050	12,300	Explosion (greased ends)
Dolomite	15B //	3.02	1.000	8,400	Explosion (Plate XV)
	15A //	1.96	0.960	8,750	Explosion
	15AA ⊥	3.02	1.000	5,100	Thud (parted on cherty bedding plane)
	15BB ⊥	3.02	1.000	3,600	Thud "
	15DD ⊥	2.73	1.010	5,350	" "
Conglomerate	14C //	2.37	0.907	21,150	Explosion (Plate XVII)
	14B //	3.00	0.960	20.600	Explosion
	14D //	2.04	0.911	17,580	"
	14DD ⊥	2.08	0.980	21,200	Explosion (Plate XVI)

PLATE IX, STRESS-STRAIN DIAGRAM, LIMESTONE (17HH) 1

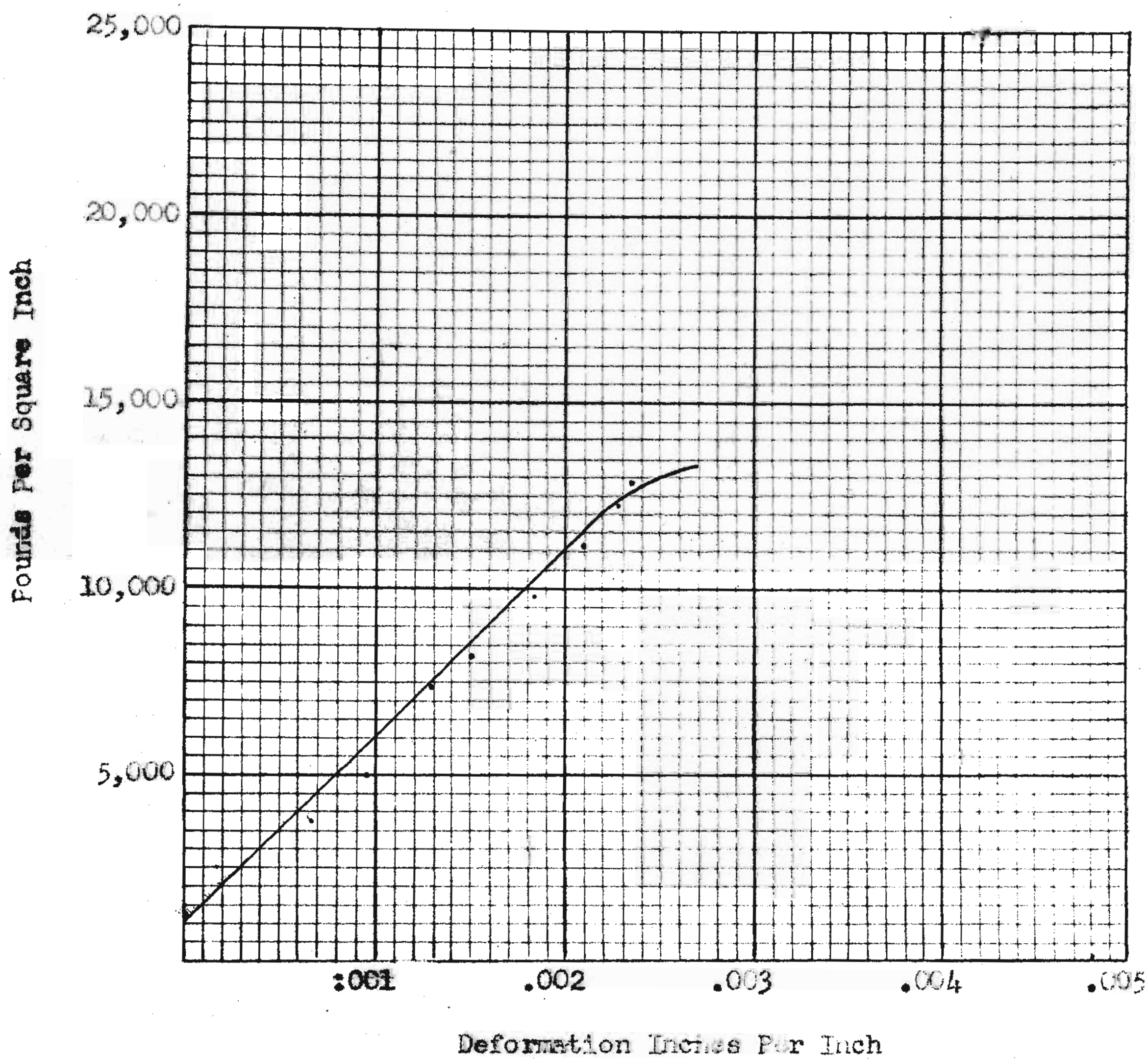


Elastic Limit = 12,000 Pounds Per Square Inch

Modulus of Elasticity = 5.2×10^6 Pounds Per Square Inch

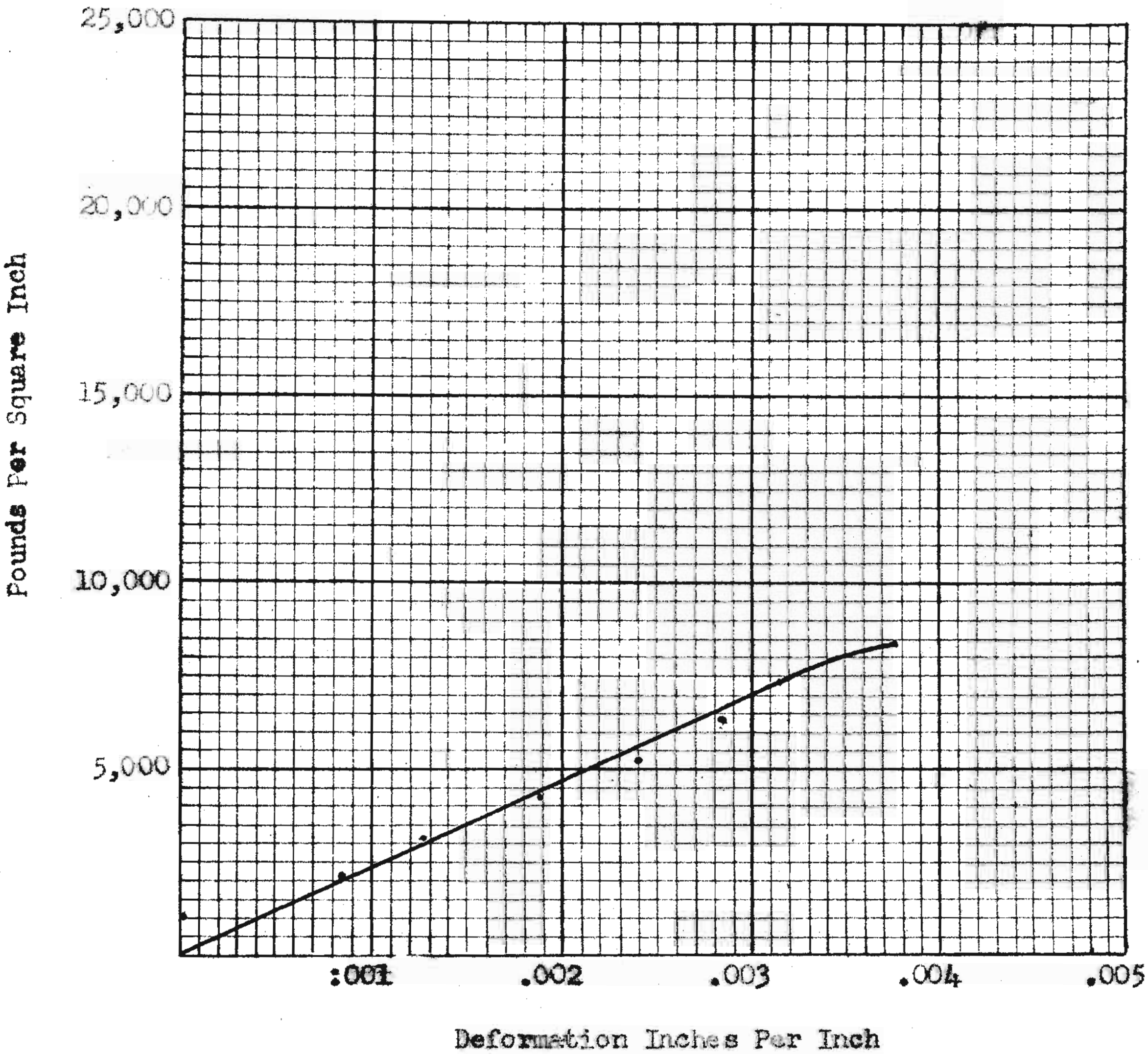
Modulus of Resilience = 14 Inch-Pounds Per Cubic Inch

PLATE X, STRESS-STRAIN DIAGRAM, LIMESTONE (17S) //



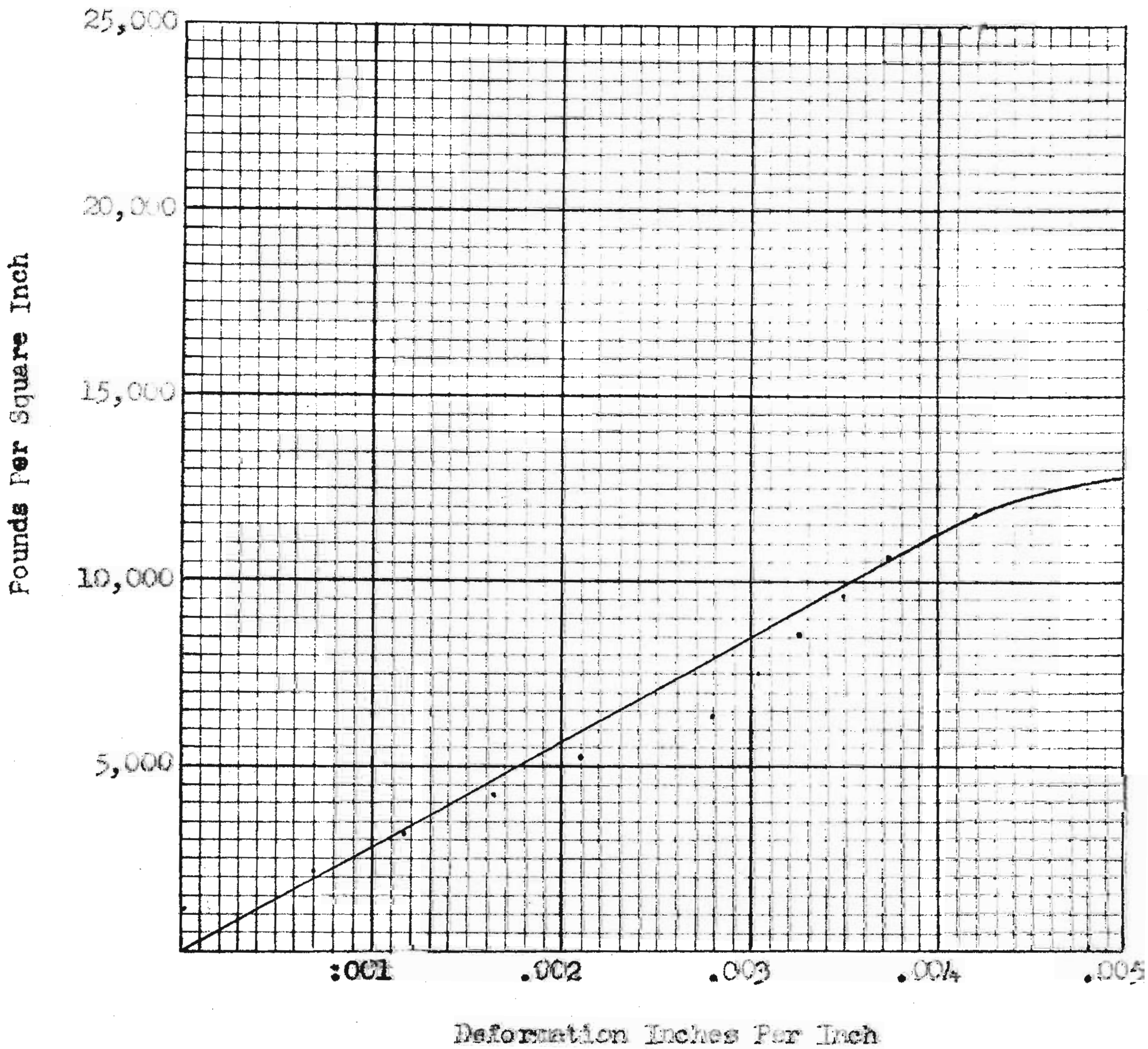
Elastic Limit =	12,000	Pounds Per Square Inch
Modulus of Elasticity =	5.1×10^6	Pounds Per Square Inch
Modulus of Resilience =	14	Inch-Pounds Per Cubic Inch

PLATE XI, STRESS-STRAIN DIAGRAM, SANDSTONE (11DD) /



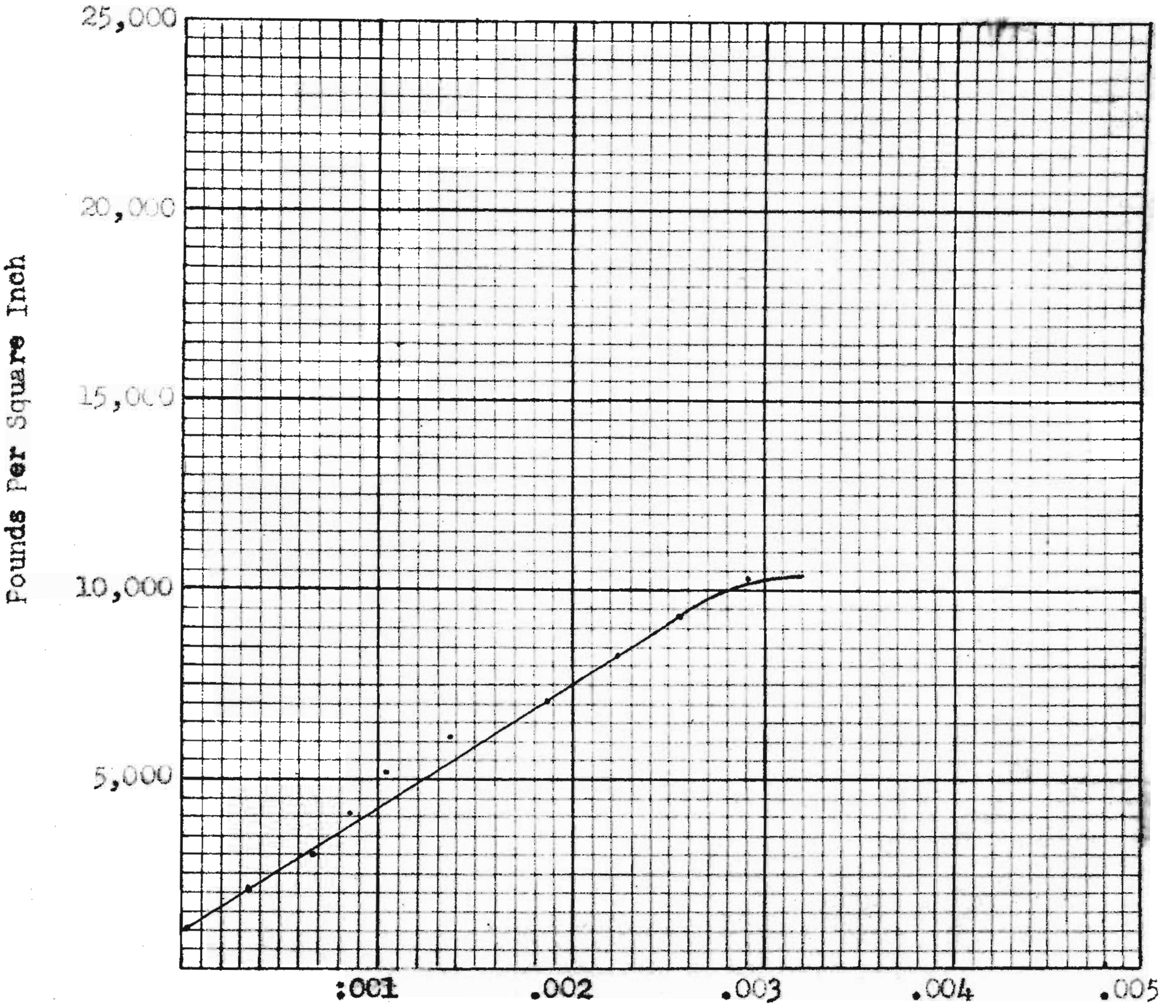
Elastic Limit =	7,400	Pounds Per Square Inch
Modulus of Elasticity =	2.3×10^6	Pounds Per Square Inch
Modulus of Resilience =	12	Inch-Pounds Per Cubic Inch

PLATE XII, STRESS-STRAIN DIAGRAM, SANDSTONE (11C) //



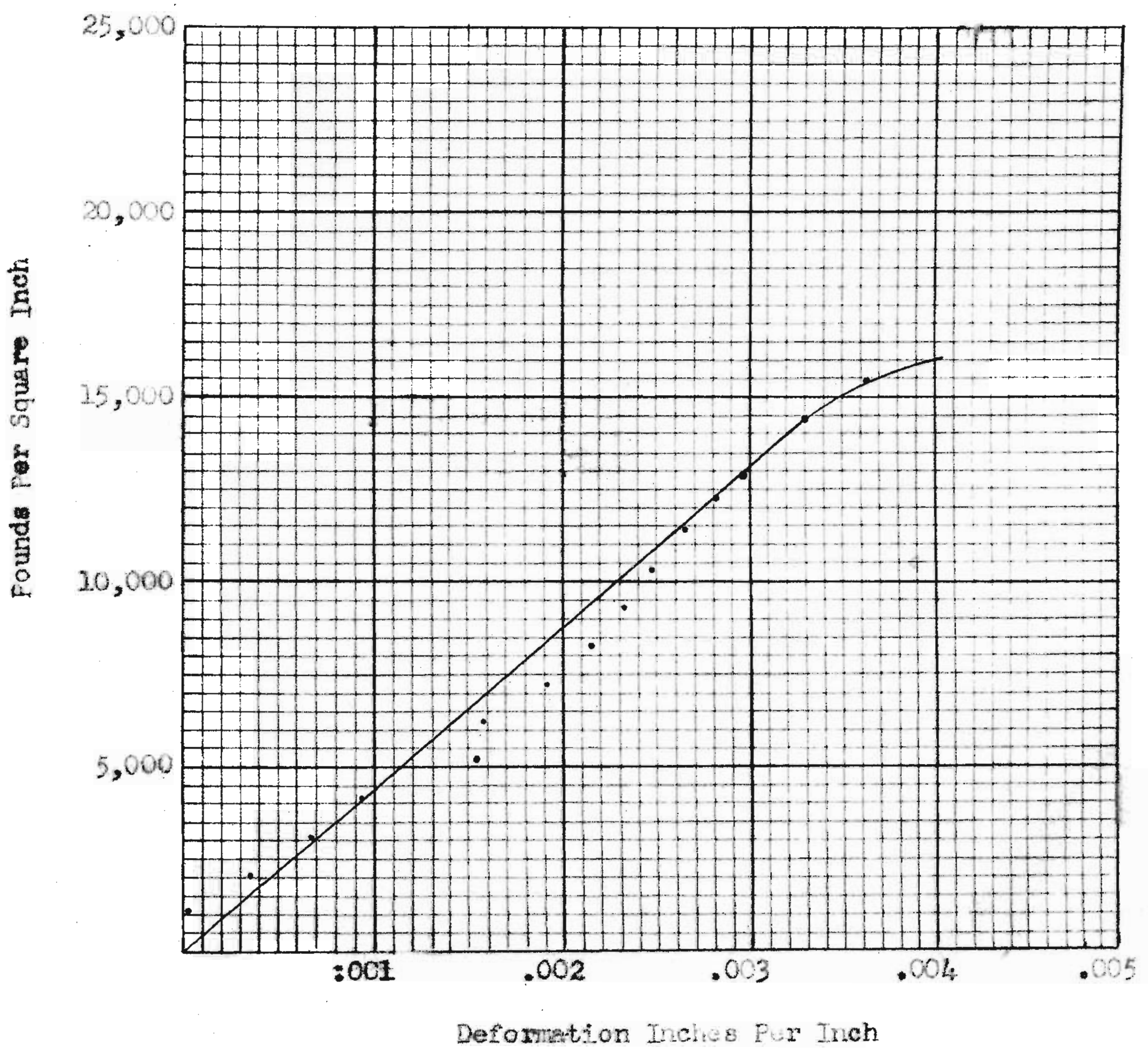
Elastic Limit =	11,250	Pounds Per Square Inch
Modulus of Elasticity =	$2.8x10^6$	Pounds Per Square Inch
Modulus of Resilience =	22	Inch-Pounds Per Cubic Inch

PLATE XIII, STRESS-STRAIN DIAGRAM, SHALE 22G //



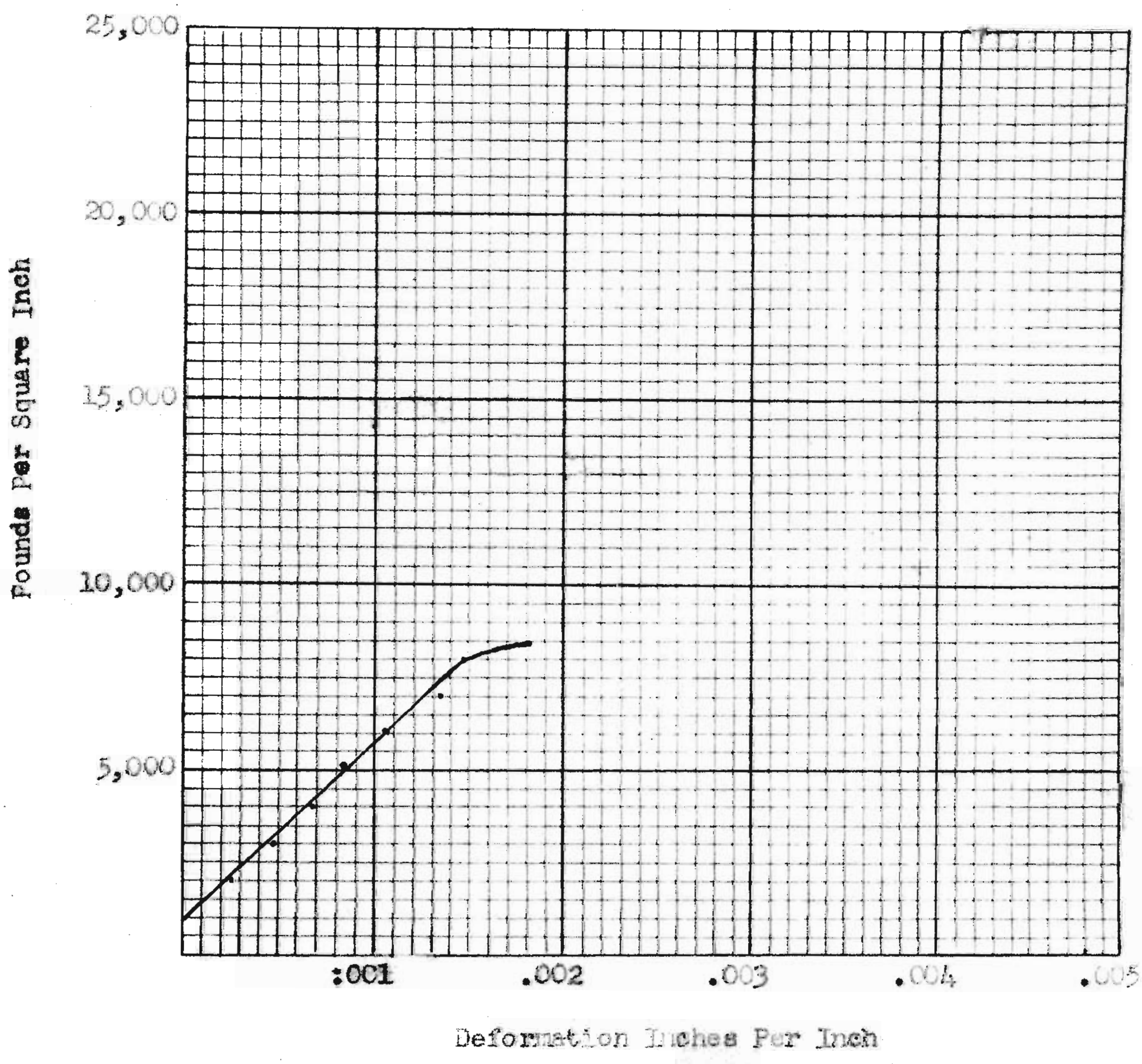
Elastic Limit =	9,300	Pounds Per Square Inch
Modulus of Elasticity =	3.2×10^6	Pounds Per Square Inch
Modulus of Resilience =	13	Inch-Pounds Per Cubic Inch

PLATE XIV, STRESS-STRAIN DIAGRAM, GRANITE (23B)



Elastic Limit =	14,400	Pounds Per Square Inch
Modulus of Elasticity =	4.3×10^6	Pounds Per Square Inch
Modulus of Resilience =	24	Inch-Pounds Per Cubic Inch

PLATE XV, STRESS-STRAIN DIAGRAM, DOLOMITE (15B) //

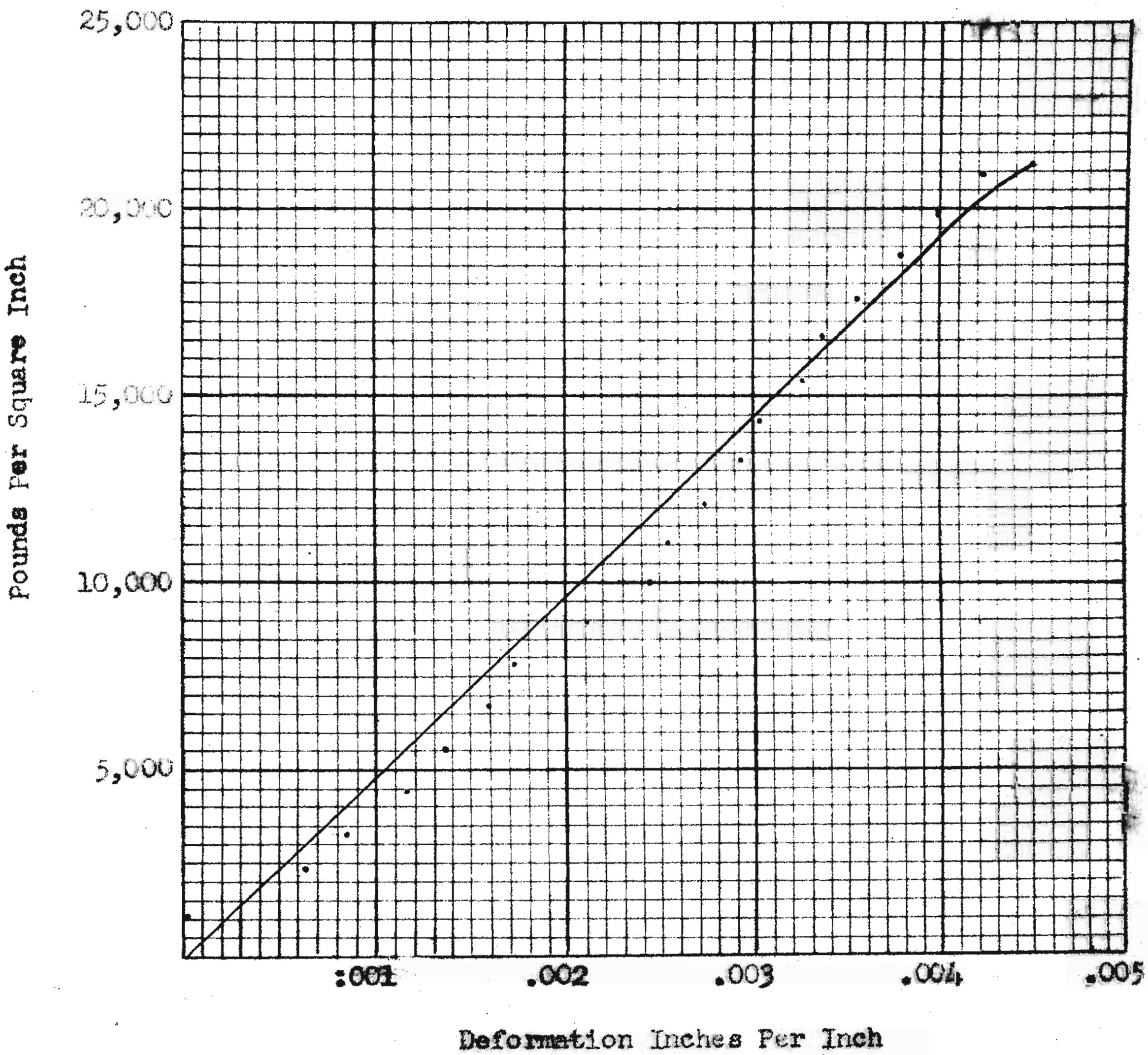


Elastic Limit = 7,500 Pounds Per Square Inch

Modulus of Elasticity = 4.8×10^6 Pounds Per Square Inch

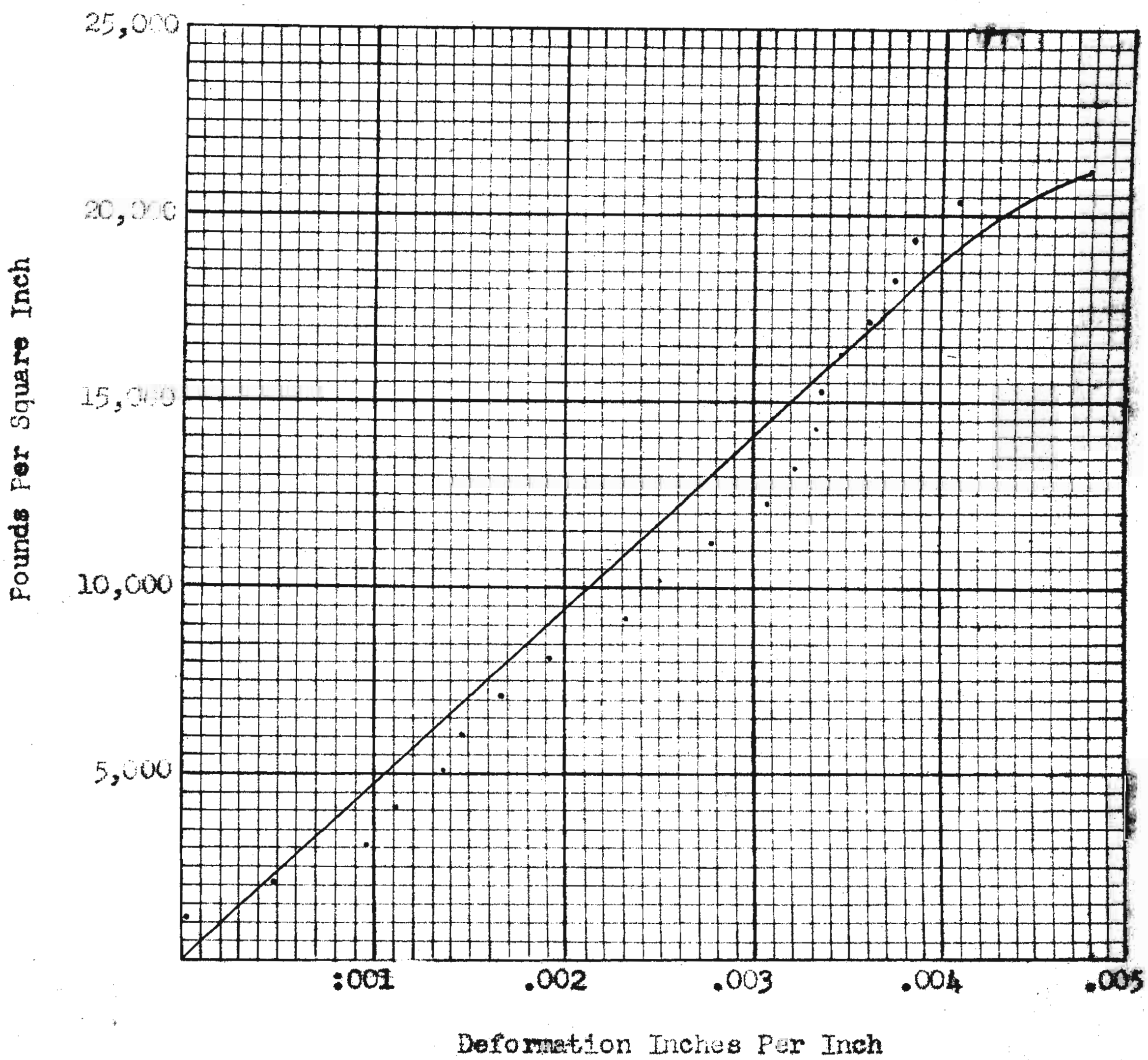
Modulus of Resilience = 6 Inch-Pounds Per Cubic Inch

PLATE XVI STRESS-STRAIN DIAGRAM, CONGLOMERATE (14C) //



Elastic Limit =	19,250	Pounds Per Square Inch
Modulus of Elasticity =	4.8×10^6	Pounds Per Square Inch
Modulus of Resilience =	38	Inch-Pounds Per Cubic Inch

PLATE XVII, STRESS-STRAIN DIAGRAM, CONGLOMERATE, 14DD/



Elastic Limit = 19,250 Pounds Per Square Inch

Modulus of Elasticity = 4.8×10^6 Pounds Per Square Inch

Modulus of Resilience = 38 Inch-Pounds Per Cubic Inch

ANGLE OF CONING AND MANNER OF RUPTURE

General

Any theory of the manner of the failure of rocks under stress must assume that the material being stressed is a perfectly homogeneous body without joints, fractures, or initial internal stresses. However, a sample of rock, no matter how small, is likely to have microscopic fractures and flaws, inasmuch as there is no rock that has not been under some strain since its formation. If the strain has not been by an imposed differential force, it has been, at least, that caused by the weight of overlying rocks with which the rock in question was associated in the earth's crust. Therefore, even though an apparently homogeneous rock may be selected as the sample specimen for testing, it will have microscopic fractures, and certainly some initial internal stresses in practically all cases. A rock even before testing in the machine has a permanent set caused by stresses acting over a long period of time.

Maximum-Strain Theory

Boyd[13/] states, "The maximum-strain theory, sometimes called St. Venant's theory, assumes that a solid reaches its elastic limit when the unit deformation reaches a given limit and that there is an ultimate unit deformation which cannot be exceeded without rupture, no matter in what way the stresses are applied which cause the deformation..........The tensile strength of some materials is much smaller than the compressive strength. If the ratio of the tensile strength to the compressive strength is less than Poisson's ratio for the material, a compressive load should cause failure by tension. This is what seems to happen with porcelain

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13/ Boyd, James E., 4th ed., N. Y. McGraw-Hill, 1935, pp. 449-450 and concrete. A porcelain rod, 1 inch in diameter and 16 inches long, supported a compressive load of 20,000 per square inch and failed by splitting lengthwise. When porcelain is tested in tension, the heads of the specimen, must be much larger than the minimum section, or the specimen will fail at the grips......

The behavior of porcelain under stress strongly supports the maximum strain theory for brittle materials."

On a rock specimen a compressive force acting parallel to the length of the specimen causes a lateral deformation of the rock in directions perpendicular to the force. This lateral deformation increases the width of the specimen and tends to decrease its length, and, if the rock is perfectly square, the deformation will be theoretically equal. A rock ordinarily is much stronger in compression than it is in tension, and failure in compression by the maximum-strain theory should be by transverse tension, or in other words, by a tensile force acting at right angles to the compressive force. Theoretically, this is impossible if the stress is acting axially, as there is no component of the compressive stress acting in the direction of the tensile force. Bridgman[14] feels that it is necessary to distinguish between an extension (strain) failure, and a tension (stress) failure, and the term used for ruptures of this kind is "extension fracture".

The extension fracture is aligned in the direction of the applied compressive force, and, if the specimen where directly in tension, the fracture would be at right angles to the tensile force. Testing rocks in tension by means of clamping the specimen in the machine would not give a satisfactory test unless that portion of the rock within the clamp

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14/ Bridgman, P.W., Vol. 9, pp. 517-528 (1938) was made larger to off-set the deformation which would result from the squeezing, compressive force of the clamp. Such compression would have to be applied in order to grasp the rock when a tensional stress was exerted. That is, the compressive forces would cause an elongation of the specimen by creating a lateral "extension" deformation in the direction of the tensile force and this would directly decrease the amount of deformation that the specimen could stand before rupturing by the tensile force. (See Fig. 8.)

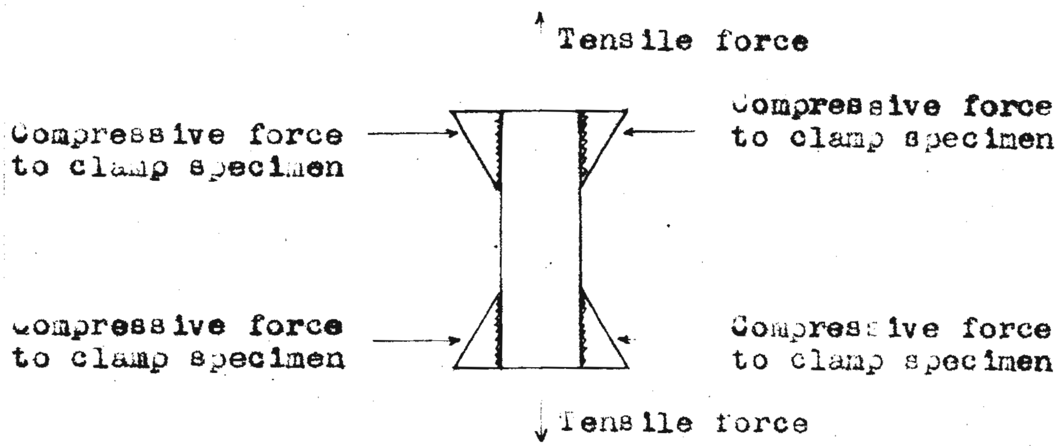

Figure 7. Rock in Tension.

In view of these difficulties which must be overcome in making direct tensile tests and, as there have been no standardized procedures developed for making tensional determinations, the modulus of rupture of a rock may be considered to indicate the ultimate strength of the rock in tension.

Rocks, when ruptured under a compressive force, usually cone at the top or bottom with extension fractures forming below or above the plane of the cone. The angle of coning as determine in the foregoing investigations seems to be constant in many rocks, but the shales developed various angles of coning. Specimen number 22G ruptured with extension fractures with the ends polished. This led to the testing of specimens of shale with ends oiled, greased, and roughed. A summary of the tests follows:

Specimen 22GG, ends rough, coned at 36°.

Specimen 22BB, ends oiled, coned at 65°.

Specimen 22CC, ends greased, ruptured by extension fractures.

Specimen 22G, end polished, ruptured by extension fractures.

Additional tests made on granite give somewhat the same results.

Specimen 23X, ends greased, ruptured by extension fractures.

Specimen 23Y, ends greased, ruptured by extension fractures.

Specimen 23A, ends ground, no polishing, 65° cone.

The above tests seem to establish a definite relationship between the angle of coning, and the rigidity with which the end is held by friction on the head of the compression machine. Rigidly held ends will cone the specimen; but specimens free to deform under the compression head will fail by extension fractures.

The tendency for specimens to cone under compression may explain the differences of strength between different length specimens[15/]. The control that specimen length exercises over the ultimate stress is caused directly by rigidly held ends. Holding the ends rigid will cause a cone at both top and bottom of the specimen. If these cones tend to intersect and overlap one another, the rock is held by a confining force, and the compressive stress must be greater than the ultimate strength of the material to overcome this confining pressure. Sample number 23 0 of granite 0.90" long reached an ultimate stress of 23,150 pounds per square inch before rupturing. Specimens 3 inches long rupture at approximately

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15/ Johnson, J. B., 6th ed., N.Y. Wiley, 1925, pp. 112-117

15,000 pounds per square inch. A test specimen with rigidly held ends and a length equal to its least transverse dimension will develop a greater ultimate strength than a specimen with a length 6 times its least transverse dimension. A 3-inch length specimen gives an ultimate strength close to the average ultimate strength developed by all specimen lengths[16].

The tests indicate that the angle of coning is controlled not by the rock composition, but by the amount of friction between the ends of the specimen and the head of the compression machine. If the discussion were to be carried further and consider the rock under a confining pressure with ends held rigid, the coning would then approach a shear and be controlled by the composition of the material.

The controlling factor of rigid and loose ends is best illustrated by a series of diagrams given in Figures 8 and 9.

Summary

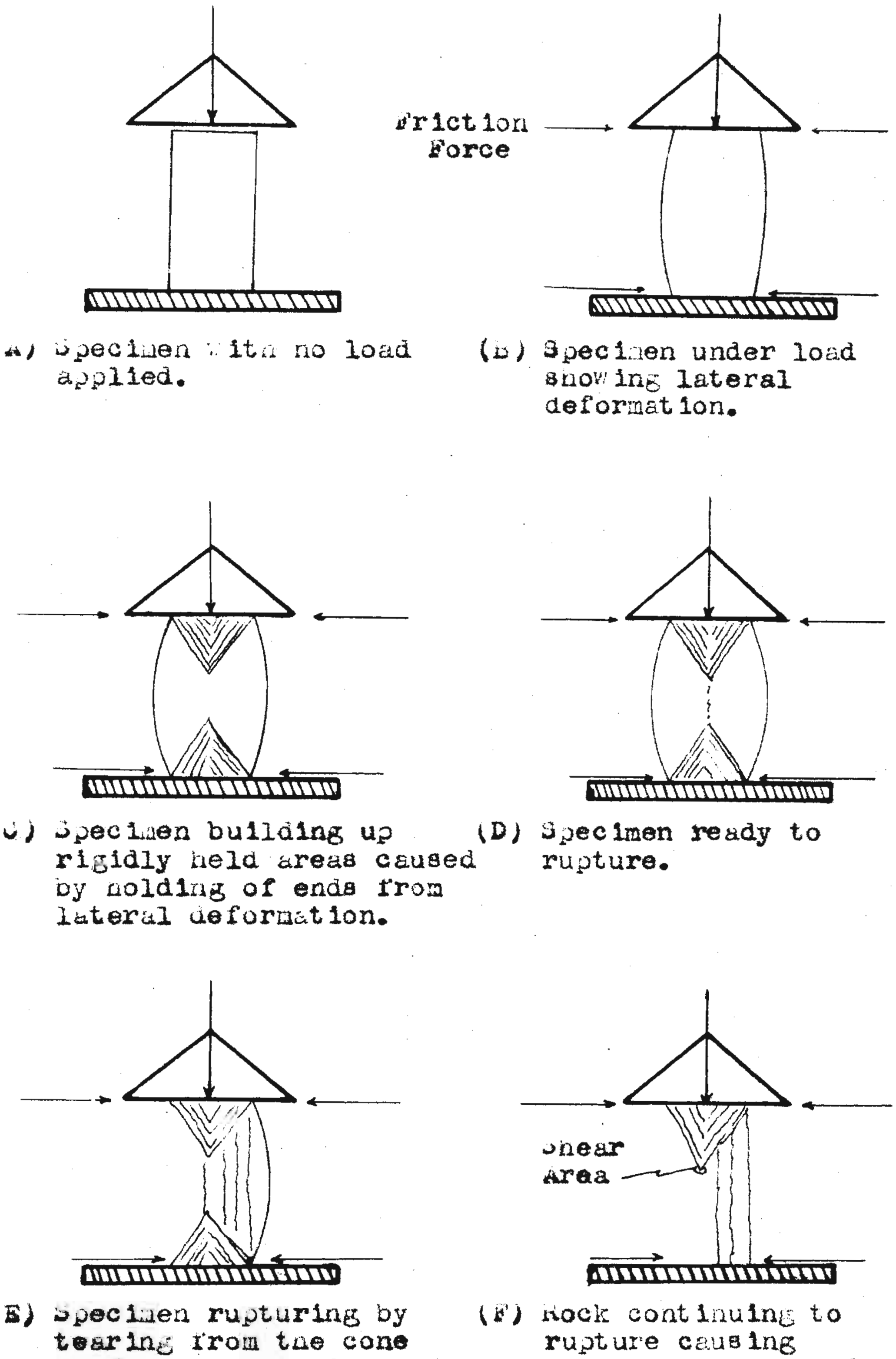
The foregoing discussion indicates that:

1. Rocks appear to fail according to the maximum-strain theory.

2. The coning angle is controlled by the amount of friction between the head of the machine and the end of the specimen.

3. The ultimate strength of a specimen is controlled by its length. A 3-inch length specimen gives an ultimate strength close to the average ultimate strength developed by all specimen lengths.

16/ Johnson, J. B., 6th ed., N. Y. Wiley, 1925. pp. 112-117



(A) Specimen with no load applied.

(B) Specimen under load showing lateral deformation.

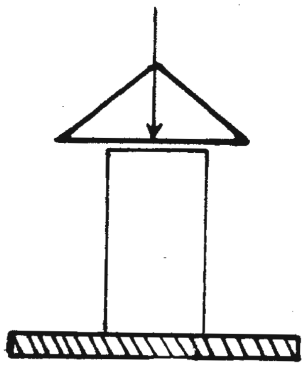
(C) Specimen building up rigidly held areas caused by holding of ends from lateral deformation.

(D) Specimen ready to rupture.

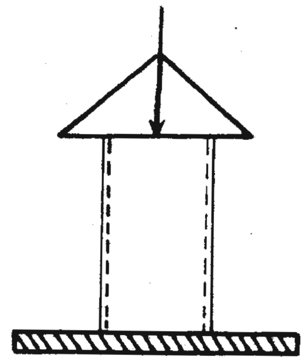
(E) Specimen rupturing by tearing from the cone surface and strain on the extension fracture.

(F) Rock continuing to rupture causing shear planes on end of the cone.

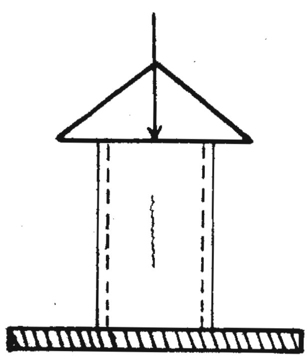
Figure 8. Specimen with ends held rigid.



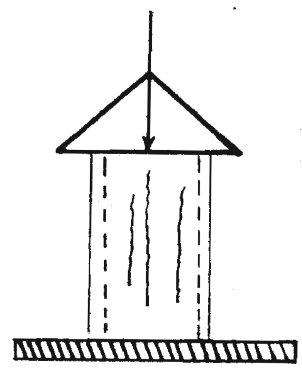
(A) Specimen with no force applied.



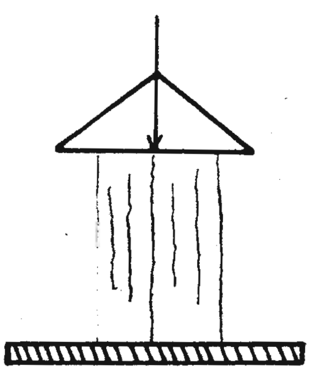
(B) Specimen under load showing lateral deformation equally throughout the specimen.



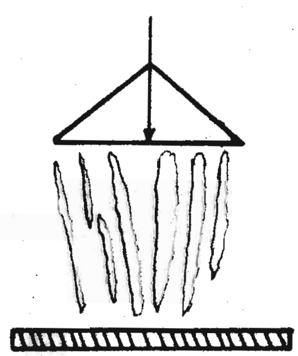
(C) Specimen beginning to rupture.



(D) Specimen developing extension fractures



(E) Specimen failure by extension fractures.



(F) Specimen explodes.

Figure 9. Specimen with ends free to move.

SUMMARY

Rocks appear to fail according to the "maximum-strain theory", which assumes that rocks reach their elastic limit when the unit deformation reaches a given limit, and that there is an ultimate unit deformation that cannot be exceeded without rupture, regardless of how the stresses that caused the deformation are applied. When rocks fail by strain they develop extension fractures parallel to the direction of the applied force. When a small specimen is tested in the laboratory, however, friction between the end of the specimen and the head of the compression machine causes the rock to cone, thus usually preventing the development of extension fractures through the entire length of the specimen.

A 1 inch by 1 inch by 3 inch test specimen is the most satisfactory size for determining the unit deformation and ultimate strength of a rock. The tests on any rock type are considered to be complete when a specimen explodes at rupture and plots in a uniform curve in the stress-strain diagram. The mechanical properties of the rock are determined by the stress-strain diagram.

APPENDIX A

DESCRIPTION OF TESTED ROCKS

The rock descriptions that follow were made megascopically with a hand lens.

Carthage Limestone (sample #17)

A white, uniform rock consisting of irregular grains of calcite of medium size cemented by very fine-grained calcite. No other minerals were observed.

Lamotte Sandstone (sample #11)

A buff colored, soft, compact, medium-grained rock, composed of clear quartz grains with more or less calcareous or magnesian material as the cement.

Shale (sample #22)

A fine-grained shale with small seams of coal on the bedding planes.

Granite (sample #23)

A holocrystalline granite used as building stone.

The most abundant mineral is feldspar and next in importance is quartz. Mica (biotite) is speckled throughout the mass giving a mottled appearance.

Dolomite (sample #15)

A medium gray, soft, cherty dolomite. The chert stringers are closely parallel to the bedding planes of the rock.

Conglomerate (Catherine Mines) (sample #14)

A partially metamorphosed limestone surrounding fragments of harder material. The harder material was not identified.

Porphyry (sample #24)

A reddish colored, hard, flinty rock. The groundmass is dense and very fine-grained, almost a glass. Large phenocrysts of quartz and feldspar are dispersed through the groundmass.

APPENDIX B

LIST OF SYMBOLS

When a symbol is associated with a certain test, it is given a subscript, for example; S_r = modulus of rupture;

S_e = elastic limit.

A - area (sq.inches)

b - width (inches)

c - distance from neutral axis to the outermost fibers of the beam (inches)

d - deformation (inches per inch)

E - modulus of elasticity (lbs. per sq.in.)

H - Maximum shear stress (pounds per square inch)

I - moment of inertia (inches^4)

L - length (inches)

M - maximum bending moment

P - load (pounds)

R_1 - left reaction in a beam (pounds)

R_2 - right reaction in a beam (pounds)

S - stress (lbs. per sq. in.)

S_e - elastic limit (lbs. per sq. in.)

S_r - modulus of rupture (pounds per sq. in.)

U - modulus of resilience (in.-lbs. per cu.in.)

V - vertical shear (pounds)

Z - section modulus (inches^3)

APPENDIX C

DATA SHEETS

The records of the tests that have been discussed are contained in this appendix. The rock type and description that corresponds to the sample number is listed in Appendix A.

Specimens that were tested with the force applied parallel to the bedding planes are marked (//) and a single letter; and those tested perpendicular to the bedding planes are marked ($\underline{/}$) and a double letter. The alphabetical letters give the order of testing.

Several specimens burst at the explosion point, into many fragments. In such cases, the particles, from which the angle of coning was determined, necessarily were fitted together to make a measurement of the angle. The sketch that accompanies each data sheet shows the principal fracture pattern that developed when rupturing was accomplished.

Sketch of Fracture

Sample No. 17 S
Force Applied: //
X-sect: 1.009" x 0.807"
Length: 3.00"
Area: 0.814 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1.000	1,230	0.00000	
0.0001	1,500	1,840	0.00030	
0.0005	2,000	2,455	0.00016	
0.0015	2,500	3,070	0.00050	
0.0020	3,000	3,685	0.00067	
0.0022	3,500	4,300	0.00073	
0.0028	4,000	4,914	0.00093	
0.0029	4,500	5,530	0.00097	
0.0030	5,000	6,140	0.00100	
0.0035	5,500	6,755	0.00117	
0.0038	6,000	7,371	0.00127	
0.0040	6,500	7,985	0.00133	
0.0045	7,000	8,600	0.00150	
0.0050	7,500	9,215	0.00167	
0.0055	8,000	9,830	0.00183	
0.0060	8,500	10,450	0.00200	
0.0062	9,000	11,055	0.00207	
0.0065	9,500	11,670	0.00217	
0.0068	10,000	12,285	0.00227	
0.0070	10,500	12,900	0.00233	
	10,900	13,390		Explosion

Sketch of Fracture

65^{o}

Sample No. 17 H
Force Applied: //
X-sect: 1.037" x 0.990"
Length: 6.97"
Area: 1.026 sq. in.
Loading: Axial

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	975	0.00000	
0.0010	1,500	1,460	0.00014	
0.0018	2,000	1,950	0.00026	
0.0025	2,500	2,435	0.00036	
0.0030	3,000	2,925	0.00043	
0.0038	3,500	3,410	0.00054	
0.0050	4,000	3,860	0.00071	
0.0060	4,500	4,385	0.00086	
0.0065	5,000	4,875	0.00093	
0.0068	5,500	5,360	0.00097	
0.0075	6,000	5,850	0.00107	
0.0080	6,500	6,335	0.00114	
0.0085	7,000	6,825	0.00107	
0.0090	7,500	7,310	0.00128	
0.0105	8,000	7,800	0.00150	
0.0110	8,500	8,285	0.00157	
0.0115	9,000	8,770	0.00164	
0.0120	9,500	9,260	0.00171	
0.0130	10,000	9,750	0.00186	
0.0140	10,500	10,230	0.00200	
0.0150	11,000	10,720	0.00214	

Continuation of Sample No. 17 H

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0155	11,500	11,210	0.00221	
0.0160	12,000	11,695	0.00229	
0.0170	12,500	12,185	0.00243	
0.0180	13,000	12,670	0.00259	
	13,250	12,915		Explosion

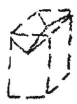
Sketch of Fracture

65° cone

Sample No. 17 T
Force Applied: //
X-sect: 1.000" x 0.808"
Length: 3.02"
Area: 0.808 sq. in.
Loading: Axial

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,240	0.00000	
0.0010	1,500	1,855	0.00036	
0.0015	2,000	2,475	0.00050	
0.0020	2,500	3,095	0,00067	
0.0025	3,000	3,710	0.00083	
0.0028	3,500	4,330	0.00092	
0.0030	4,000	4,950	0.00100	
0.0035	4,500	5,570	0.00116	
0.0038	5,000	6,190	0.00123	
0.0040	5,500	6,805	0.00133	
0.0050	6,000	7,425	0.00167	
0.0060	6,500	8,045	0.00200	
	7,200	8,910		Fractured Longi-tudinally.
0.0075	7,500	9,280	0.00250	
	7,700	9,530		Partial Explosion.

Sketch of Fracture



65° cone

Sample No. 17 A
Force Applied: //
X-sect: 1.012" x 1.023"
Length: 2.98"
Area: 1.035 sq. in.
Loading: Axial

Defor-mation inches	Forces (P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	2,000	1,930	0.00000	
0.0000	3,000	2,900	0.00000	
0.0010	4,000	3,860	0.00034	
0.0015	5,000	4,830	0.00050	
0.0020	6,000	5,800	0.00067	
0.0025	7,000	6,750	0.00084	
0.0030	8,000	7,730	0.00100	
0.0035	9,000	8,700	0.00118	Piece cracked from one corner.
0.0065	10,000	9,660	0.00218	
	10,400	10,050		Partial Explosion.

<u>Sketch of Fracture</u>

65° cone

Sample No. 17 R
Force Applied: //
X-sect; 1.005" x 1.024"
Length: 2.95
Area: 1.029 sq.in.
Loading: Axial

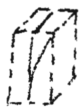
Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	**Remarks**
0.0000	1,000	971	0.00000	
0.0010	1,500	1,455	0.00034	
0.0015	2,000	1,945	0.00051	
0.0020	2,500	2,430	0.00068	
0.0025	3,000	2,915	0.00085	
0.0029	3,500	3,400	0.00098	
0.0032	4,000	3,885	0.00108	
0.0039	4,500	4,373	0.00132	Longitudinal fracturefull length.
	4,900	4,760		Pieces spalled from corners.
0.0055	5,000	4,860	0.00186	
0.0060	5,500	5,345	0.00203	
0.0063	6,000	5,830	0.00213	
0.0065	6,500	6,315	0.00220	
0.0070	7,000	6,800	0.00237	
0.0073	7,500	7,290	0.00247	
0.0076	8,000	7,775	0.00258	
0.0080	8,500	8,260	0.00271	
0.0085	9,000	8,745	0.00288	
0.0090	9,500	9,230	0.00305	
0.0095	10,000	9,720	0.00322	

Continuation of Sample No. 17 R

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	10,300	10,010		Explosion

Sketch of Fracture

65°



Sample No. 17 N
Force Applied: //
X-sect: 1.018" x 1.023"
Length: 3.02"
Area: 1.041 sq. in.
Loading: Axial

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	960	0.00000	
0.0010	1,500	1,440	0.00033	
0.0012	2,000	1,920	0.00040	
0.0015	2,500	2,400	0.00050	
0.0020	3,000	2,880	0.00066	
0.0022	3,500	3,350	0.00072	
0.0025	4,000	3,840	0.00083	
0.0030	4,500	4,320	0.00100	
0.0035	5,000	4,800	0.00120	
0.0040	5,500	5,280	0.00130	
0.0050	6,000	5,760	0.00160	
0.0060	6,500	6,240	0.00200	Longitudinal fracture
0.0075	7,000	6,720	0.00250	
0.0080	7,500	7,205	0.00270	
0.0085	8,000	7,685	0.00280	
0.0090	8,500	8,165	0.00300	
0.0095	9,000	8,645	0.00310	
0.0100	9,500	9,125	0.00330	
0.0110	10,000	9,600	0.00360	
0.0112	10,500	10,080	0.00370	
0.0115	11,000	10,570	0.00380	
	11,500	11,050		Broke longitudinally. Partial explosion.

<u>Sketch of Fracture</u>

65 °
Back from
corner

Sample No. 17 U
Force Applied: //
X-sect: 0.994" x 0.881"
Length: 4.04"
Area: 0.876 sq. in.
Loading: Eccentric

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,140	0.00000	
0.0005	1,500	1,710	0.00012	
0.0010	2,000	2,285	0.00025	
	2,400	2,739		Thud. Rock failed suddenly with no warning.

Sketch of Fracture

65°
Back from
corner

Sample No. 17 V
Force Applied: //
X-sect: 0.890" x 1.010"
Length: 6.07"
Area: 0.899 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,110	0.00000	
0.0010	1,500	1,670	0.00016	
0.0012	2,000	2,225	0.00020	
0.0020	2,500	2,780	0.00033	
0.0022	3,000	3,340	0.00036	
0.0028	3,500	3,895	0.00046	
0.0033	4,000	4,450	0.00055	
0.0038	4,500	5,005	0.00063	
0.0048	5,000	5,560	0.00080	
	5,100	5,670		Thud.

Sketch of Fracture

65°

Sample No. 17 J
Force Applied: //
X-sect: 0.975" x 1.000"
Length: 9.03"
Area: 0.975 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,025	0.00000	
0.0001	1,500	1,540	0.00011	
0.0015	2,000	2,050	0.00017	
0.0025	2,500	2,565	0.00028	
0.0035	3,000	3,075	0.00039	
0.0050	3,500	3,590	0.00055	
0.0060	4,000	4,100	0.00067	
0.0070	4,500	4,615	0.00077	
0.0075	5,000	5,130	0.00083	
0.0085	5,500	5,640	0.00094	
0.0095	6,000	6,155	0.00105	
0.0105	6,500	6,665	0.00116	Longitudinal fracture through complete length.
0.0120	7,000	7,180	0.00133	Bending. Thud.

Sketch of Fracture

75°

Sample No. 17 C
Force Applied: //
X-sect: 0.915" x 1.011"
Length: 3.07"
Area: 0.935 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,081	0.00000	
0.0000	1,500	1,620	0.00000	
0.0005	2,000	2,160	0.00016	
0.0015	2,500	2,702	0.00049	Fractured longitudinally.
0.0020	3,000	3,240	0.00065	
0.0020	3,500	3,780	0.00065	
0.0021	4,000	4,325	0.00068	
0.0025	4,500	4,865	0.00083	
0.0029	5,000	5,405	0.00096	Corner sheared off.
0.0033	5,500	5,945	0.00107	
0.0035	6,000	6,485	0.00114	
0.0040	6,500	7,025	0.00132	
0.0050	7,000	7,565	0.00165	
0.0055	7,500	8,110	0.00182	
	7,900	8,540		Thud.

<u>Sketch of Fracture</u>

67°

Sample No. 17 D
Force Applied: //
X-sect: 1.019" x 1.023"
Length: 3.00"
Area: 1.042 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	960	0.00000	
0.0010	1,500	1,440	0.00033	
0.0015	2,000	1,920	0.00050	
0.0019	2,500	2,400	0.00063	
0.0025	3,000	2,880	0.00083	
0.0029	3,500	3,350	0.00097	
0.0032	4,000	3,840	0.00107	
0.0040	4,500	4,320	0.00133	
0.0050	5,000	4,800	0.00167	
0.0060	5,500	5,380	0.00200	
0.0075	6,000	5,760	0.00250	
0.0080	6,500	6,240	0.00267	
0.0150	7,000	6,720	0.00300	
	7,400	7,100		Fractured longitudinally.

Sketch of Fracture

85°

Sample No. 17 P
Force Applied: //
X-sect: 1.027" x 0.888"
Length: 3.05"
Area: 0.912 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,096	0.00000	
0.0005	1,500	1,645	0.00016	
0.0010	2,000	2,190	0.00033	
0.0015	2,500	2,740	0.00050	
0.0019	3,000	3,290	0.00063	
0.0023	3,500	3,840	0.00076	
0.0030	4,000	4,385	0.00100	
0.0035	4,500	4,935	0.00117	
				Fractured longi-tudinally
0.0050	5,000	5,480	0.00167	
0.0055	5,500	6,030	0.00183	
0.0060	6,000	6,580	0.00200	
0.0062	6,500	7,125	0.00207	
	6,800	7,455		Thud

Sketch of Fracture

Sample No. 17 B
Force Applied: //
X-sect: 0.999" x 1.019"
Length: 2.00"
Area: 1.018 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	980	0.00000	
0.0005	2,000	1,960	0.00025	
0.0020	3,000	2,950	0.00100	
0.0025	4,000	3,930	0.00135	
0.0039	5,000	4,910	0.00185	
0.0070	5,900	5,790	0.00350	Fractured longi-tudinally.
0.0120	6,100	5,990	0.00600	
0.0130	6,800	6,680	0.00650	Thud

Sketch of Fracture

Sample No. 17 C
Force Applied: //
X-sect: 0.986" x 0.974"
Length: 2.01"
Area: 0.960 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq in.	d in/in.	Remarks
0.0000	1,000	1,040	0.00000	
0.0010	1,500	1,560	0.00050	
0.0018	2,000	2,080	0.00089	
0.003	2,500	2,610	0.00149	
0.0045	3,000	3,130	0.00224	
0.0055	3,500	3,640	0.00274	
0.0060	4,000	4,160	0.00298	
0.0062	4,500	4,690	0.00308	
0.0068	5,000	5,210	0.00338	
0.0070	5,500	5,730	0.00348	
0.0072	6,000	6,250	0.00358	
0.0078	6,500	6,770	0.00388	
0.0079	7,000	7,290	0.00393	
0.0085	7,500	7,810	0.00423	Longitudinal crack developed.
0.0115	8,000	8,330	0.00572	
0.0120	8,300	8,640	0.00597	Thud. Fractured longitudinally.

Sketch of Fracture

Sample No. 17 K
Force Applied: //
X-sect: 0.938" x 0.978"
Length: 3.57"
Area: 0.917 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,090	0.00000	
0.0010	1,500	1,635	0.00028	
0.0015	2,000	2,180	0.00042	
0.0020	2,500	2,725	0.00056	
0.0022	3,000	3,270	0.00062	
0.0025	3,500	3,815	0.00070	
0.0030	4,000	4,360	0.00084	
	4,100	4,470		Fractured longi-tudinally.
0.0050	4,500	4,900	0.00140	
	5,100	5,560		Thud.

Sketch of Fracture

Sample No. 17 M
Force Applied: //
X-sect: 0.875" x 1.017"
Length: 5.02"
Area: 0.890 sq. in.
Loading: Eccentric

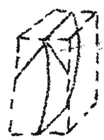
Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	2,000	2,250	0.00000	
0.0010	2,500	2,810	0.00019	
0.0020	3,000	3,370	0.00039	
0.0025	3,500	3,930	0.00050	
0.0040	4,000	4,495	0.00080	
	4,200	4,720		Fractured longi-tudinally.
0.0075	4,500	5,055	0.00149	
	4,600	5,170		Thud.

Sketch of Fracture

Sample No. 17 W
Force Applied: //
X-sect: 1.009" x 0.865"
Length: 7.10"
Area: 0.873 sq. in.
Loading: Eccentric

Deformation inches	Forces (P) lbs.	Stress (S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,145	0.00000	
0.0005	1,500	1,718	0.00007	
0.0010	2,000	2,290	0.00014	
0.0015	2,500	2,865	0.00021	
0.0020	3,000	3,435	0.00029	
0.0025	3,500	4,010	0.00036	
0.0030	4,000	4,580	0.00043	
0.0035	4,500	5,155	0.00050	
0.0050	5,000	5,730	0.00071	Fractured longitudinally.
0.0060	5,500	6,300	0.00086	
0.0070	6,000	6,870	0.00100	
0.0075	6,500	7,445	0.00107	
	6,900	7,905		Fractured longitudinally in 3 pieces. Thud.

Sketch of Fracture

60°  57°

Sample No.: 17 I
Force Applied: //
X-sect: 1.035" x 1.040"
Length: 8.03"
Area: 1.076 sq. in.
Loading: Eccentric

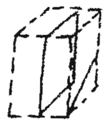
Deformation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	930	0.00000	
0.0015	1,500	1,395	0.00019	
0.0030	2,000	1,860	0.00037	
0.0045	2,500	2,320	0.00056	
0.0065	3,000	2,790	0.00081	
0.0070	3,500	3,250	0.00087	
0.0075	4,000	3,720	0.00094	
0.0110	4,500	4,180	0.00137	
	4,700	4,370		Fracturerd longitudinally near top of specimen.
0.0160	5,000	4,640	0.00199	
0.0210	5,400	5,020	0.00262	Curved fracture developed. Thud.

Sketch of Fracture

Sample No. 17 Y
Force Applied: //
X-sect: 0.910" x 1.020"
Length: 8.09"
Area: 0.928 sq. in.
Loading: Eccentric

Defor-mation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,078	0.00000	
0.0005	1,500	1,616	0.00006	
0.0010	2,000	2,155	0.00012	
0.0012	2,500	2,695	0.00013	
0.0020	3,500	3,770	0.00022	
0.0025	4,000	4,310	0.00026	
0.0028	4,500	4,850	0.00031	
0.0031	5,000	5,390	0.00033	
0.0040	5,500	5,925	0.00047	
0.0045	6,000	6,465	0.00050	
0.0050	6,500	7,005	0.00055	
0.0060	7,000	7,540	0.00067	
0.0068	7,500	8,080	0.00075	
0.0070	8,000	8,620	0.00078	
0.0078	8,500	9,160	0.00087	
	8,900	9,590		Thud. Fractured longitudinally.

Sketch of Fracture



60^{o}
crushed bottom
broken off corners

Sample No. 17 Q
Force Applied: //
X-sect: 0.811" x 1.000"
Length: 3.03"
Area: 0.811 sq. in.
Loading: Eccentric

Deformation inches	Forces(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,235	0.00000	
0.0005	1,500	1,850	0.00017	
0.0009	2,000	2,465	0.00030	
0.0010	2,500	3,080	0.00033	
	2,800			Fractured longitudinally.
0.0020	3,000	3,700	0.00067	
0.0025	3,500	4,315	0.00083	
0.0030	4,000	4,930	0.00099	
0.0035	4,500	5,550	0.00117	
0.0040	5,000	6,165	0.00133	
0.0060	5,500	6,780	0.00198	
0.0065	6,000	7,400	0.00217	
0.0068	6,500	8,015	0.00227	
0.0070	7,000	8,630	0.00233	
	7,100	8,755		Thud.

Sketch of Fracture

61°

Sample No. 17 E
Force Applied: //
X-sect: 1.028" x 1.005"
Length: 3.92 sq. in.
Area: 1.033
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	970	0.00000	
0.0015	1,500	1,450	0.00038	
0.0020	2,000	1,940	0.00051	
0.0028	2,500	2,420	0.00071	
0.0030	3,000	2,900	0.00076	
0.0040	3,500	3,390	0.00102	
0.0050	4,000	3,870	0.00127	
0.0055	4,500	4,350	0.00139	
0.0060	5,000	4,840	0.00153	
0.0065	5,500	5,320	0.00165	Piece spalled off side.
0.0070	6,000	5,810	0.00178	
0.0080	6,500	6,230	0.00204	
0.0090	7,000	6,775	0.00229	
0.0100	7,500	7,260	0.00255	
0.0110	8,000	7,745	0.00279	
0.0115	8,500	8,230	0.00293	
0.0120	8,900	8,620	0.00306	Thud. Fractured longitudinally.

<u>Sketch of Fracture</u>

60°

Sample No. 17 X
Force Applied: //
X-sect: 1.026" x 1.005"
Length: 4.98"
Area: 1.031 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	970	0.00000	
0.0015	1,500	1,450	0.00030	
0.0020	2,000	1,940	0.00040	
0.0025	2,500	2,420	0.00050	
0.0030	3,000	2,900	0.00060	
0.0035	3,500	3,390	0.00070	
0.0040	4,000	3,870	0.00080	
0.0050	4,600	4,460	0.00100	
0.0055	5,000	4,840	0.00110	
0.0060	5,500	5,320	0.00120	
0.0060	6,000	5,810	0.00120	
0.0060	6,500	6,230	0.00120	
0.0065	7,000	6,775	0.00130	
0.0068	7,500	7,260	0.00136	
0.0070	8,000	7,445	0.00140	
0.0075	8,500	8,230	0.00150	
0.0090	8,600	8,340	0.00180	Thud.

Sketch of Fracture

Sample No. 17 G
Force Applied: //
X-sect: 1.018" x 1.050"
Length: 6.00"
Area: 1.069 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	935	0.00000	
0.0020	1,500	1,405	0.00033	
0.0070	2,000	1,870	0.00116	
0.0075	2,500	2,340	0.00126	
0.0080	3,000	2,810	0.00133	
0.0085	3,500	3,275	0.00141	
0.0090	4,000	3,740	0.00150	
0.0100	4,500	4,210	0.00167	
0.0100	5,000	4,675	0.00167	
0.0105	5,500	5,145	0.00175	
0.011	6,000	5,610	0.00183	
0.0113	6,500	6,080	0.00188	
0.0115	7,000	6,550	0.00191	
0.0118	7,500	7,015	0.00197	
0.0120	8,000	7,485	0.00200	
0.0130	8,500	7,950	0.00217	
0.0140	9,000	8,420	0.00233	
	9,100	8,512		Thud. Fractured longitudinaly

Sketch of Fracture

66° cone

Sample No. 17 AA
Force Applied: /
X-sect: 1.012" x 1.003"
Length: 2.90"
Area: 1.01 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	965	0.00000	
0.0005	2,000	1,930	0.00017	
0.0010	3,000	2,900	0.00035	
0.0015	4,000	3,870	0.00052	
0.0020	5,000	4,830	0.00069	
0.0025	6,000	5,800	0.00087	
0.0028	7,000	6,760	0.00097	
0.0030	8,000	7,730	0.00104	
0.0035	9,000	8,700	0.00121	
0.0040	10,000	9,650	0.00139	
0.0048	11,000	10,600	0.00166	
0.0050	12,000	11,600	0.00173	
0.0060	13,000	12,550	0.00208	
0.0065	14,000	13,500	0.00225	
	14,500	14,000		Explosion.

Sketch of Fracture

66°

Sample No. 17 BB
Force Applied:
X-sect: 1.016" x 0.989"
Length: 2.92"
Area: 1.00 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,000	0.00000	
0.0010	2,000	2,000	0.00033	
0.0018	3,000	3,000	0.00061	
0.0022	4,000	4,000	0.00075	
0.0028	5,000	5,000	0.00097	
0.0030	6,000	6,000	0.00103	
0.0035	7,000	7,000	0.00120	
0.0040	8,000	8,000	0.00137	
0.0045	9,000	9,000	0.00154	
0.0050	10,000	10,000	0.00171	
0.0055	11,000	11,000	0.00189	
0.0060	12,000	12,000	0.00205	
0.0068	13,000	13,000	0.00233	
	13,450	13,450		Explosion.

Sketch of Fracture

Sample No. 17 CC
Force Applied: /
X-sect: 1.016" x 1.014"
Length: 2.89"
Area: 1.03 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	970	0.00000	
0.0010	2,000	1,940	0.00035	
0.0020	3,000	2,910	0.00069	
0.0035	4,000	3,880	0.00121	
0.0060	5,000	4,860	0.00208	
	6,600	6,400		Spalled and broke. Thudded softly.

Sketch of Fracture

Sample No. 17 DD
Force Applied: /
X-sect: 1.006" x 1.003"
Length: 2.88"
Area: 1.01 sq. in.
Loading: Eccentric

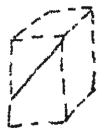
Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	985	0.00000	
0.0030	2,000	1,970	0.00104	
0.0050	3,000	2,950	0.00174	
0.0060	4,000	3,940	0.00208	
0.0070	5,000	4,920	0.00243	
0.0075	6,000	5,900	0.00260	Spalling.
	6,700	6,600		Thud.

Sketch of Fracture

Sample No. 17 EE
Force Applied: /
X-sect: 1.011" x 0.996"
Length: 2.90"
Area: 1.01 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	990	0.00000	
0.0015	2,000	1,990	0.00052	
0.0030	3,000	2,970	0.00104	
0.0065	4,000	3,960	0.00224	
0.0075	5,000	4,950	0.00258	
0.0090	6,000	5,940	0.00310	
	6,700	6,640		Thud.

Sketch of Fracture



66°

Sample No. 17 FF
Force Applied: /
X-sect: 1.008" x 1.000"
Length: 2.90"
Area: 1.008 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	993	0.00000	
0.0015	2,000	1,990	0.00052	
0.0020	3,000	2,980	0.00069	
0.0025	4,000	3,970	0.00096	
0.0030	5,000	4,960	0.00107	
0.0035	6,000	5,950	0.00121	
0.0040	7,000	6,950	0.00138	
0.0050	8,000	7,940	0.00173	
0.0055	9,000	8,940	0.00190	
0.0060	10,000	9,930	0.00207	
0.0065	11,000	10,920	0.00224	
0.0070	12,000	11,910	0.00241	
0.0075	13,000	12,900	0.00258	
	13,100	13,000		Explosion.

Sketch of Fracture

66°

Sample No. 17 GG
Force Applied: /
X-sect: 1.010" x 1.035"
Length: 2.93"
Area: 1.04 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	980	0.00000	
0.0000	2,000	1,960	0.00000	
0.0010	3,000	2,940	0.00034	
0.0015	4,000	3,920	0.00052	
0.0020	5,000	4,900	0.00068	
0.0024	6,000	5,880	0.00082	
0.0028	7,000	6,860	0.00096	
0.0031	8,000	7,850	0.00106	
0.0038	9,000	8,830	0.00130	
0.0040	10,000	9,800	0.00137	
0.0050	11,000	10,780	0.00170	
0.0060	12,000	11,760	0.00204	
0.0065	13,000	12,750	0.00222	
0.0070	14,000	13,720	0.00239	Explosion.

Sketch of Fracture

66°

Sample No. 17 HH
Force Applied: /
X-sect: 1.028" x 1.050"
Length: 2.87"
Area: 1.08 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	925	0.00000	
0.0015	2,000	1,850	0.00052	
0.0018	3,000	2,780	0.00063	
0.0020	4,000	3,700	0.00070	
0.0025	5,000	4,625	0.00087	
0.0028	6,000	5,550	0.0098	
0.0030	7,000	6,480	0.00105	
0.0036	8,000	7,400	0.00125	
0.0040	9,000	8,320	0.00139	
0.0045	10,000	9,250	0.00157	
0.0050	11,000	10,200	0.00174	
0.0055	12,000	11,100	0.00192	
0.0060	13,000	12,030	0.00209	
0.0065	13,500	12,500	0.00226	
0.0068	14,000	12,950	0.00237	
0.0072	14,800	13,700	0.00251	Explosion.

Sketch of Fracture

57°

Sample No. 11 A
Force Applied: //
X-sect: 1.028" x 0.960"
Length: 3.00"
Area: 0.99 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,010	0.00000	
0.0018	2,000	2,020	0.00060	
0.0028	3,000	3,030	0.00093	
0.0038	4,000	4,040	0.00127	
0.0050	5,000	5,050	0.00167	
0.0060	6,000	6,060	0.00200	
0.0065	7,000	7,070	0.00217	
0.0070	8,000	8,080	0.00234	
0.0078	9,000	9,090	0.00260	
0.0085	10,000	10,110	0.00284	
	10,700	10,810		Explosion.

Sketch of Fracture

Sample No. 11 B
Force Applied: //
X-sect: 1.038" x 1.025"
Length: 2.87"
Area: 1.06 sq. in.
Loading: Eccentric

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	940	0.00000	Weathered.
0.0020	2,000	1,880	0.00069	
0.0032	3,000	2,830	0.00112	
0.0050	4,000	3,780	0.00174	
0.0063	5,000	4,720	0.00220	
	5,800	5,460		Fractured down middle of specimen.
0.0100	6,000	5,650	0.00349	
0.0115	7,000	6,600	0.00402	
0.0140	7,700	7,260	0.00488	Thud.

Sketch of Fracture

Sample No. 11 C
Force Applied: //
X-sect: 0.962" x 0.976"
Length: 2.14"
Area: 0.94"
Loading:

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,080	0.00000	
0.0015	2,000	2,130	0.00070	
0.0025	3,000	3,200	0.00116	
0.0035	4,000	4,260	0.00163	
0.0045	5,000	5,320	0.00210	
0.0060	6,000	6,400	0.00280	
0.0065	7,000	7,450	0.00303	
0.0070	8,000	8,510	0.00326	
0.0075	9,000	9,560	0.00350	
0.0080	10,000	10,640	0.00373	
0.0090	11,000	11,700	0.00420	
0.0110	11,900	12,680	0.00514	Explosion.

Sketch of Fracture

Sample No. 11 D
Force Applied: //
X-sect: 1.024" x 0.959"
Length: 2.40"
Area: 0.98 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,020	0.00000	Weathered.
0.0020	2,000	2,040	0.00083	
0.0030	3,000	3,060	0.00125	
0.0040	4,000	4,080	0.00167	
0.0050	5,000	5,100	0.00208	
0.0060	6,000	6,120	0.00250	
0.0070	7,000	7,140	0.00292	
0.0080	7,900	8,060	0.00334	Explosion.

Sketch of Fracture

Sample No. 11 AA
Force Applied: ⁄
X-sect: 1.000" x 1.000"
Length: 2.52"
Area: 1.00 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,000	0.00000	Weathered.
0.0020	2,000	2,000	0.00079	
0.0028	3,000	3,000	0.00111	
0.0038	4,000	4,000	0.00151	
0.0050	5,000	5,000	0.00199	
0.0065	6,000	6,000	0.00258	
0.0072	7,000	7,000	0.00286	
0.0085	8,000	8,000	0.00348	
	8,200	8,200		Did not explode completely. Semi-thud.

Sketch of Fracture

Sample No. 11 BB
Force Applied: /
X-sect: 1.033" x 0.960"
Length: 2.35"
Area: 0.99 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,010	0.00000	Weathered.
0.0015	2,000	2,020	0.00064	
0.0025	3,000	3,030	0.00107	
0.0040	4,000	4,040	0.00170	
0.0055	5,000	5,050	0.00234	
0.0065	6,000	6,060	0.00278	
	6,900	6,960		Thud.

Sketch of Fracture

Sample No. 11 CC
Force Applied: /
X-sect: 0.995" x 0.990"
Length: 2.36"
Area: 0.985 sq. in.
Loading: Eccentric

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,020	0.00000	Weathered.
0.0013	2,000	2,040	0.00055	
0.0020	3,000	3,060	0.00085	
0.0030	4,000	4,080	0.00127	
0.0040	5,000	5,100	0.00170	
0.0055	6,000	6,120	0.00234	
0.0065	7,000	7,140	0.00278	
	7,200	7,340		Thud.

Sketch of Fracture

Sample No. 11 DD
Force Applied: ⊥
X-sect: 0.985" x 0.965"
Length: 2.38"
Area: 0.95 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,050	0.00000	Weathered.
0.0020	2,000	2,110	0.00084	
0.0030	3,000	3,160	0.00126	
0.0045	4,000	4,210	0.00189	
0.0058	5,000	5,260	0.00240	
0.0068	6,000	6,330	0.00285	
0.0075	7,000	7,360	0.00315	
0.0090	7,950	8,360	0.00378	Explosion.

Sketch of Fracture

Sample No. 22 G
Force Applied: //
X-sect: 1.00" x 0.97"
Length: 2.92"
Area: 0.97 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,030	0.00000	
0.0010	2,000	2,060	0.00034	
0.0020	3,000	3,090	0.00068	
0.0025	4,000	4,125	0.00085	
0.0030	5,000	5,155	0.00102	
0.0040	6,000	6,185	0.00136	
0.0055	7,000	7,215	0.00188	
0.0065	8,000	8,250	0.00222	
0.0075	9,000	9,280	0.00256	
0.0085	10,000	10,310	0.00291	
	10,100	10,410		Explosion. Botton Smoothed.

Sketch of Fracture

Fragments
Wedge-shaped

Sample No. 22 F
Force Applied: //
X-sect: 0.94" x 1.00"
Length: 3.09"
Area: 0.94 sq. in.
Loading: Axial

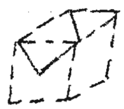
Defor-mation inches	Force(P) lbs.	Stress(S) lbs/sq. in.	d in/in.	Remarks
0.0000	1,000	1,065	0.00000	
0.0010	2,000	2,130	0.00032	
0.0018	3,000	3,190	0.00058	
0.0025	4,000	4,255	0.00081	
0.0035	5,000	5,320	0.00113	
0.0050	6,000	6,380	0.00162	
0.0065	7,000	7,445	0.00210	
0.0075	8,000	8,510	0.00243	
0.0080	8,700	9,255	0.00258	Explosion. No apparent yield point.

Sketch of Fracture

Sample No. 22 I
Force Applied: //
X-sect: 0.93" x 0.66"
Length: 3.06"
Area: 0.61 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,640	0.00000	
0.0000	2,000	3,280	0.00000	
0.0010	3,000	4,920	0.00032	
0.0020	4,000	6,560	0.00065	
0.0035	5,000	8,195	0.00114	
0.0065	6,000	9,835	0.00212	
	6,200	10,163		Explosion.

Sketch of Fracture



65° cone

Sample No. 22 BB
Force Applied: /
X-sect: 1.00" x 1.00"
Length: 1.14"
Area: 1.00 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lbs/sq. in.	d in/in.	Remarks
	11,450	11,450		Explosion. Ends oiled.

Sketch of Fracture

Sample No. 22 CC
Force Applied: /
X-sect: 1.00" x 1.00"
Length: 1.4"
Area: 1.00 sq. in.
Loading: Axial

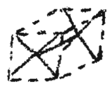
Deformation inches	Force(P) lbs.	Stress(S) lbs/ sq. in.	d in/in.	Remarks
	9,000	9,000		Explosion. Ends greased, longitudinal fracture.

Sketch of Fracture

Sample No. 22 FF
Force Applied: /
X-sect: 1.000" x 1.020"
Length: 1.03"
Area: 1.02 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	12,500	12,250		Explosion. Fragmentation with 36° cone.

Sketch of Fracture



45° cone

Sample No. 22 GG
Force Applied: /
X-sect: 0.960" x 1.020"
Length: 1.00"
Area: 0.98 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	13,200	13,490		45° cone

Sketch of Fracture

65°

Sample No. 23 A
Force Applied:
X-sect: 0.965" x 1.005"
Length: 3.00"
Area: 0.97 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,030	0.00000	
0.0015	2,000	2,060	0.00050	
0.0020	3,000	3,090	0.00067	
0.0025	4,000	4,130	0.00083	
0.0035	5,000	5,160	0.00116	
0.0040	6,000	6,180	0.00133	
0.0050	7,000	7,220	0.00167	
0.0060	8,000	8,250	0.00200	
0.0065	9,000	9,280	0.00217	
0.0070	10,000	10,300	0.00233	
0.0075	11,000	11,340	0.00250	
0.0078	12,000	12,380	0.00260	
0.0085	13,000	13,400	0.00283	
0.0090	14,000	13,420	0.00300	
0.0110	14,600	15,060	0.00367	Explosion.

Sketch of Fracture

65°

Sample No. 23 B
Force Applied:
X-sect: 1.000" x 0.969"
Length: 3.03"
Area: 0.97 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,030	0.00000	
0.0010	2,000	2,060	0.00033	
0.0020	3,000	3,090	0.00066	
0.0028	4,000	4,120	0.00092	
0.0035	5,000	5,160	0.00155	
0.0048	6,000	6,180	0.00158	
0.0058	7,000	7,220	0.00191	
0.0065	8,000	8,250	0.00214	
0.0070	9,000	9,280	0.00231	
0.0075	10,000	10,310	0.00248	
0.0080	11,000	11,350	0.00264	
0.0085	12,000	12,380	0.00281	
0.0090	13,000	13,400	0.00297	
0.0100	14,000	14,420	0.00330	
0.0110	15,000	15,480	0.00363	
	15,700	16,180		Explosion.

Sketch of Fracture

74^{o}

Polished bottom

Sample No. 23 C
Force Applied:
X-sect: 0.998" x 0.968"
Length: 2.95"
Area: 0.966 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,030	0.00000	
0.0005	2,000	2,070	0.00017	
0.0010	3,000	3,100	0.00034	
0.0015	4,000	4,140	0.00058	
0.0020	5,000	5,160	0.00068	
0.0028	6,000	6,210	0.00095	
0.0032	7,000	7,250	0.00108	
0.0040	8,000	8,280	0.00136	
0.0050	9,000	9,320	0.00169	
0.0055	10,000	10,360	0.00187	
0.0060	11,000	11,400	0.00204	
0.0065	12,000	12,420	0.00220	
0.0070	13,000	13,480	0.00237	
	13,400	13,800		Explosion.

Sketch of Fracture

Sample No. 23 D
Force Applied:
X-sect: 1.00" x 1.00"
Length: 0.90"
Area: 1.00 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	23,150	23,150		Broke into wedge fragments (pulverized). Explosion.

Sketch of Fracture

Sample No. 23 X
Force Applied;
X-sect: 1.00" x 1.02"
Length: 4.00"
Area: 1.02 sq. in.
Loading: Axial

Defor- mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	12,000	11,760		Explosion. Greased ends. Fractured longitudinally.

Sketch of Fracture

Sample No. 23 Y
Force Applied:
X-sect: 1.00" x 1.05"
Length: 4.00"
Area: 1.05 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
	12,900	12,300		Explosion. Greased ends. Fractured longitudinally.

Sketch of Fracture

Sample No. 15 A
Force Applied: //
X-sect: 0.945" x 1.020"
Length: 1.96"
Area: 0.96 Sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,040	0.00000	
0.0005	2,000	2,080	0.00017	
0.0013	3,000	3,130	0.00044	
0.0018	4,000	4,160	0.00061	
0.0025	5,000	5,210	0.00085	
0.0030	6,000	6,250	0.00102	
0.0035	7,000	7,290	0.00118	
0.0040	8,000	8,340	0.00135	
	8,400	8,750		Bulged at middle. Explosion.

Sketch of Fracture

Sample No. 15 B
Force Applied: //
X-sect: 0.075" x 1.025"
Length: 3.02
Area: 1.00 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,000	0.00000	
0.0008	2,000	2,000	0.00026	
0.0015	3,000	3,000	0.00049	
0.0020	4,000	4,000	0.00066	
0.0025	5,000	5,000	0.00083	
0.0032	6,000	6,000	0.00106	
0.0040	7,000	7,000	0.00133	
0.0045	8,000	8,000	0.00149	
	8,400	8,400		Explosion.

Sketch of Fracture

Sample No.	15 AA
Force Applied :	/
X-sect:	0.978" x 1.019"
Length:	3.02"
Area:	1.00 sq. in.
Loading:	

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,000	0.00000	
0.0020	2,000	2,000	0.00066	
0.0030	3,000	3,000	0.00099	
0.0050	4,000	4,000	0.00165	
0.0060	5,000	5,000	0.00198	
	5,100	5,100		Thud. Parted on cherty bedding plane.

Sketch of Fracture

Sample No. 15 BB
Force Applied:
X-sect: 0.980" x 1.018"
Length: 3.02"
Area: 1.00 sq. in.
Loading:

Defor-mation inches	Force (P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,000	0.00000	
0.0020	2,000	2,000	0.00066	
0.0035	3,000	3,000	0.00116	
	3,600	3,600		Soft thud. Parted on cherty bedding plane.

Sketch of Fracture	
Sample No.	15 DD
Force Applied:	/
X-sect:	0.997" x 1.013"
Length:	2.73"
Area:	1.01 sq. in.
Loading:	

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	990	0.00000	
0.0020	2,000	1,980	0.00073	
0.0030	3,000	2,970	0.00110	
0.0040	4,000	3,960	0.00147	
0.006	5,000	4,950	0.00220	
	5,400	5,350		Parted on cherty bedding planes.

Sketch of Rupture

66° cone

Sample No. 14 B
Force Applied: //
X-sect: 0.975" x 0.990"
Length: 3.00"
Area: 0.96 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,040	0.00000	
0.0010	2,000	2,080	0.00033	
0.0015	3,000	3,120	0.00050	
0.0018	4,000	4,160	0.00060	
0.0020	5,000	5,200	0.00067	
0.0022	6,000	6,200	0.00073	
0.0028	7,000	7,290	0.00093	
0.0030	8,000	8,330	0.00100	
0.0032	9,000	9,360	0.00107	
0.0036	10,000	10,400	0.00120	
0.0040	11,000	11,450	0.00133	
0.0045	12,000	12,500	0.00150	
0.0050	13,000	13,540	0.00167	
0.0055	14,000	14,580	0.00183	
0.0060	15,000	15,610	0.00200	
0.0062	16,000	16,650	0.00207	
0.0068	17,000	17,700	0.00227	
0.0070	18,000	18,750	0.00233	
0.0072	19,000	19,780	0.00240	
0.0090	19,800	20,600	0.00300	Spalled at 19,-700. Explosion.

Sketch of Fracture

Sample No. 14 C
Force Applied: //
X-sect: 0.965" x 0.940"
Length: 2.37"
Area: 0.907 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,100	0.00000	
0.0015	2,000	2,200	0.00063	
0.0020	3,000	3,300	0.00084	
0.0028	4,000	4,400	0.00118	
0.0032	5,000	5,500	0.00135	
0.0038	6,000	6,610	0.00160	
0.0042	7,000	7,710	0.00172	
0.0050	8,000	8,810	0.00211	
0.0058	9,000	9,920	0.00245	
0.0060	10,000	11,000	0.00253	
0.0065	11,000	12,100	0.00274	
0.0070	12,000	13,200	0.00295	
0.0072	13,000	14,310	0.00303	Side spalled off at 13,000.
0.0078	14,000	15,410	0.00329	
0.0080	15,000	16,510	0.00338	
0.0085	16,000	17,610	0.00358	
0.0090	17,000	18,710	0.00380	
0.0095	18,000	19,810	0.00400	
0.0100	19,000	20,910	0.00422	
	19,200	21,150		Explosion.

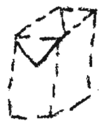
Sketch of Fracture

68° cone

Sample No. 14 D
Force Applied: //
X-sect: 0.985" x 1.006"
Length: 2.04"
Area: 0.991 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,010	0.00000	
0.0010	2,000	2,010	0.00049	
0.0015	3,000	3,020	0.00073	
0.0018	4,000	4,040	0.00088	
0.0022	5,000	5,050	0.00107	
0.0025	6,000	6,060	0.00122	
0.0028	7,000	7,070	0.00137	
0.0032	8,000	8,080	0.00156	
0.0035	9,000	9,090	0.00171	
0.0040	10,000	10,100	0.00196	
0.0045	11,000	11,100	0.00220	
0.0045	12,000	12,120	0.00234	
0.0050	13,000	13,130	0.00245	Spalled.
0.0060	14,000	14,140	0.00294	
0.0065	15,000	15,150	0.00318	
0.0068	16,000	16,160	0.00333	
0.0070	17,000	17,170	0.00343	
	17,400	17,580		Explosion.

Sketch of Fracture

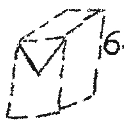


65° cone

Sample No. 14 CC
Force Applied: /
X-sect: 0.991" x 0.984"
Length: 2.03"
Area: 0.975 sq. in.
Loading: Axial

Defor-mation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,025	0.00000	
0.0015	2,000	2,050	0.00074	
0.0023	3,000	3,075	0.00134	
0.0030	4,000	4,100	0.00148	
0.0033	5,000	5,125	0.00163	
0.0039	6,000	6,150	0.00192	
0.0045	7,000	7,175	0.00222	
0.0050	8,000	8,200	0.00248	
0.0057	9,000	9,225	0.00281	
0.0062	10,000	10,250	0.00306	
0.0065	11,000	11,275	0.00320	
0.0068	12,000	12,300	0.00335	
0.0070	13,000	13,325	0.00345	
0.0072	14,000	14,350	0.00355	
0.0075	15,000	15,375	0.00370	
0.0078	16,000	16,400	0.00384	
0.0080	17,000	17,425	0.00394	
0.0090	18,000	18,450	0.00444	Spalled at 17,725
0.0100	19,000	19,475	0.00492	
0.0102	20,000	20,500	0.00503	
	20,700	21,200		Explosion.

Sketch of Fracture



64° cone

Sample No. 14 DD
Force Applied: /
X-sect: 0.979" x 1.005"
Length: 2.08"
Area: 0.98 sq. in.
Loading: Axial

Deformation inches	Force(P) lbs.	Stress(S) lb/sq. in.	d in/in.	Remarks
0.0000	1,000	1,020	0.00000	
0.0010	2,000	2,040	0.00048	
0.0020	3,000	3,060	0.00096	
0.0023	4,000	4,080	0.00110	
0.0028	5,000	5,100	0.00135	
0.0030	6,000	6,120	0.00144	
0.0035	7,000	7,140	0.00168	
0.0040	8,000	8,160	0.00192	
0.0048	9,000	9,180	0.00231	
0.0052	10,000	10,200	0.00250	
0.0060	11,000	11,230	0.00288	
0.0064	12,000	12,240	0.00308	
0.0067	13,000	13,250	0.00322	
0.0069	14,000	14,300	0.00332	
0.0070	15,000	15,300	0.00336	
0.0072	16,000	16,320	0.00346	
0.0075	17,000	17,350	0.00361	
0.0078	18,000	18,380	0.00375	
0.0080	19,000	19,400	0.00385	
0.0085	20,000	20,400	0.00409	
0.0100	20,800	21,200	0.00480	Explosion.

BIBLIOGRAPHY

1. Books:

a. Billings, M.P., Structural geology. N.Y., Prentice-Hall, 1946 pp. 7-32, 99-110.

b. Boyd, James E., Strength of materials., 4th ed., N.Y., McGraw-Hill, 1935. pp. 1-104, 447-452.

c. Forrester, J. D., Principles of field and mining geology. N.Y. Wiley, 1946. pp. 17-19

d. Heiland, C. A., Geophysical exploration. N. Y., Prentice-Hall, 1940. pp. 452-483.

e. Houwink, R., Elasticity, plasticity and structure of matter. London, Cambridge, 1937. pp. 73-127.

f. Johnson, J. B., Materials of construction, rewritten by M. O. Withey and James Aston., 6th ed., N. Y. Wiley, 1925. pp. 1-139, 234-261.

g. Laurson, P. G. and Cox, W. J., Mechanics of materials. N. Y. Wiley, 1938. pp. 1-140, 280-282.

h. Nevin, C. M., Principles of structural geology, N. Y. Wiley, 1931. pp. 1-29.

i. Willis, B. and Willis, R., Geologic structures. 3rd ed., N. Y. McGraw-Hill, 1934. pp. 1-34.

j. Winston, S. E., Machine design. Chicago Am. Tech. Soc., 1944. pp. 19-44.

2. Periodicals:

a. Bridgman, P. W., Reflections on rupture. Journal of Applied Physics. Vol. 9, pp. 517-528. (1938).

3. U. S. Government Publications:

a. National Lumber Manufacturers Association. Wood structural design data, 2nd ed., Vol. 1, 1941. pp. 1-54.

b. U. S. Bureau of Mines. Standardized tests for determining the physical properties of mine rock. Report of Investigation 3891, August 1946. 67 pp.

4. State Publications:

a. Griffith, John H., physical properties of typical american rocks. Iowa Eng. Exper. Sta., Bull. 161, 1937. 56 pp.